AD-A094 689 SYSTEMS CONTROL INC (VT) PALO ALTO CA F/G 13/10
PLANNING SYSTEM IDENTIFICATION TRIALS OF WATERWAY TOWS.(U)
DEC 80 T L TRANKLE N00014-79-C-0786
UNCLASSIFIED SCI-5327-01 ONR-CR-215-276-1F NL

1 of 1
AD-
A094689

END
DATE
FILMED
3 81
DTIC

AD A094689

LEVEL II

(20)

REPORT ONR-CR-215-276-1F

OFFICE OF NAVAL RESEARCH

USN

ONR

PLANNING SYSTEM IDENTIFICATION TRIALS OF WATERWAY TOWS

Project 5327

T.L. TRANKLE

Contract No. N00014-79-C-0786

OCTOBER 1980

PREPARED FOR THE
OFFICE OF NAVAL RESEARCH • 800 N. QUINCY ST. • ARLINGTON, VA. 22217

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: ONR/CR-215-276-1F

2. GOVT ACCESSION NO.: AD-A094 684

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle): PLANNING SYSTEM IDENTIFICATION TRIALS OF WATERWAY TOWS.

5. TYPE OF REPORT & PERIOD COVERED: ENGINEERING TECHNICAL REPORT, 22 Jul [redacted]979 — 22 JUL [redacted]980

6. PERFORMING ORG. REPORT NUMBER: SCI-5327-01

7. AUTHOR(s): Thomas L. Trankle

8. CONTRACT OR GRANT NUMBER(s): N00014-79-C-0786

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
SYSTEMS CONTROL, INC. (Vt)
1801 Page Mill Road
Palo Alto, CA 94304

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS:
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. Coast Guard Headquarters
2100 2nd St. S.W., Room 4407, Washington, DC 20590

12. REPORT DATE: DECEMBER 1980

13. NUMBER OF PAGES

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
OFFICE OF NAVAL RESEARCH
800 North Quincy Road
Arlington, Virginia 22217

15. SECURITY CLASS. (of this report): UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Unlimited distribution.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

inland waterways
ship maneuvering
waterway tows
tug barge flotillas
hydrodynamic coefficients
system identification
maneuvering simulation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents a plan for determining hydrodynamic coefficients of maneuvering simulation models of river tow/barge flotillas from data collected during free-running maneuvering trials of the full-scale river tows themselves. The plan includes specification of motion sensor type and accuracy requirements and a schedule of maneuvers to be executed during trials. Simulation of the maneuvering trials and data collection indicates that the system identification statistical data processing technique can estimate hydrodynamic coefficients similar in form to those obtained from towing tank planar motion mechanism—

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT (Continued)

tests. Calculation of the sensitivity of definitive maneuvering characteristics to changes in hydrodynamic coefficients indicates coefficient estimation accuracy requirements.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

I. INTRODUCTION

This report presents a plan for determining hydrodynamic elements of maneuvering simulation models of river tow/barge flotillas from data collected during free-running maneuvering trials of the full-scale river tows themselves. Maneuvering models of ships are differential equations which represent the ship's motion response given external inputs such as rudder angle and propeller rate commands or water currents. The hydrodynamic elements of such a model calculate the forces and moments on the ship as a function of the ship's velocity with respect to the water, ship's angular rates and control (e.g. rudder, propeller rate) usage. Most existing simulations of river tows [1-5] use hydrodynamic models derived from captive scale model tow tank tests. It is possible to determine these hydrodynamic models using full-scale ship motion data (e.g. yaw rate history, velocity history, rudder angle history) recorded during the execution of test maneuvers. The determination of the hydrodynamic models from the motion data uses the system identification statistical data processing technique.

The effective use of system identification to determine models of dynamic systems requires the application of an integrated procedure for test planning, test execution, and data processing (Figure 1.1) [6]. Test planning first requires the selection of test goals. For example, what characteristics of a hydrodynamic model are needed (e.g. maneuvering only? Seakeeping?) How accurately must the model characteristics be determined? Once quantitative requirements have been determined, the test plan itself can be specified. The test plan includes a schedule of maneuvers to be executed and a set of sensor type and accuracy specifications.

Real-time data consistency evaluation can aid effective test execution. Inexpensive microcomputers can perform this . The

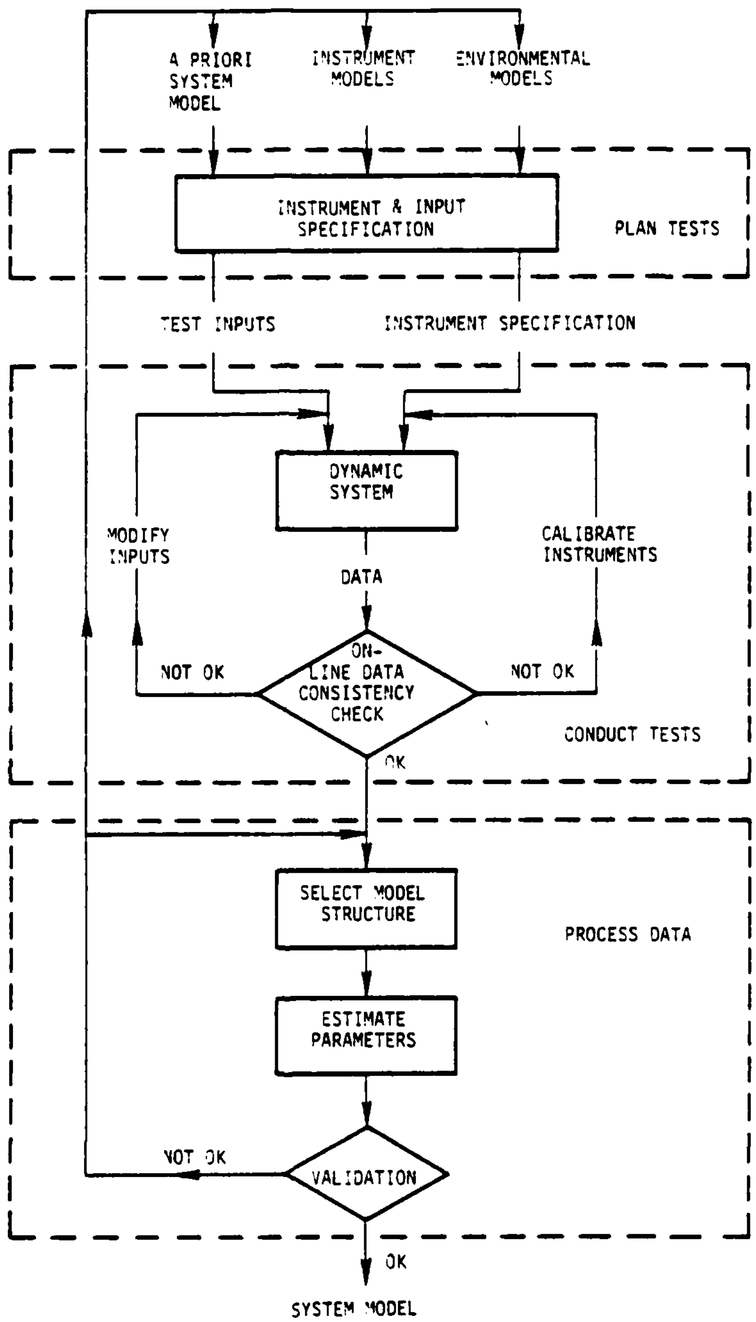

Figure 1.1 The Integrated System Identification Procedure

computer can alert test technicians to sensor failures or can recalibrate sensors as the test is being conducted.

Data processing requires validated system identification algorithms to select a model structure and to estimate values of parameters themselves. Issues addressed in the model structure determination phase [7] include the order of the model (e.g. number of degrees of freedom) and a mathematical form (e.g. multidimensional polynomial) to represent any nonlinear character in the dynamic equations. Quantitative statistical criteria exist for the relative comparison of predictive abilities of models of varying forms and levels of complexity [7]. The estimation of unknown parameter values follows the determination of a suitable model structure. Numerical values of unknown parameters are determined by choosing them to optimize some performance index which measures how well the mathematical model represents observed data.

The remainder of this report is organized as follows:

- Section II summarizes methods for the determination of hydrodynamic models of ships. This section defines the unique contributions that can be made by system identification processing of full-scale maneuvering data. It also lists the minimum data collection requirements for system identification.

- Section III defines a generic ship simulation model which can be used for modeling river tows and which can be used in conjunction with system identification model determination. This section addresses the question of how accurately the parameters of the model must be determined in order to meet reasonable simulation fidelity goals.

- Section IV evaluates several different sensor systems to be used to record river tow motion during trial maneuvers. The evaluation is based on analytical simulation studies of the river tow executing test maneuvers. The study determines how accurately several significant hydrodynamic characteristics can be estimated using several candidate systems. These attainable estimation accuracies are then compared to the accuracy requirements set forth in Section III.

- Section V presents a complete schedule of maneuvers to be executed by the river tow in order to gather information about the tow's total hydrodynamic model. An adequate schedule can be completed in approximately three days of testing at 10 hours of operation per day. A more complete schedule requires nine days of testing. This section also evaluates two potential test sites, Lake Pontchartrain and the Barkley Dam pool, with regard to available maneuvering area.

II. SURVEY OF METHODS FOR THE DETERMINATION OF HYDRODYNAMIC MODELS

In general, knowledge of hydrodynamic maneuvering models is required for the simulation of marine vehicle motion in a wide range of environments. The broader range of application of this work includes Maritime Administration (MARAD) requirements such as modeling of ship collision avoidance capabilities, modeling ship operations with a man in the control loop (performed by the Computer Aided Operations Research Facility (CAORF)), and the evolution of sea trial acceptance test specifications. United States Coast Guard (USCG) requirements relate to the study of waterway design (safety, economic impacts, and aids to navigation) and of maneuvering aids (e.g. bow thrusters).

A specific USCG requirement is for the simulation analysis of river tow/barge flotilla maneuvering on the inland waterways of the United States. Such analysis could aid decisions in the area of river tow operations regulations, river tow design, and channel design. Additionally, real-time simulation using a manned simulator such as CAORF could aid in training river tow operators.

This section will outline the three basic approaches (mathematical analysis, towing tank tests, and full-scale tests) to the determination of maneuvering hydrodynamic coefficients. The purpose is to summarize the contributions of each approach. The section on full-scale tests will pay special attention to the system identification data processing algorithms. These algorithms are required in order to develop a generalized model, such as that used by the CAORF simulator, from the specific measurement history data which result from such tests. Additionally, the fundamental measurement requirements which will permit the use of system identification of hydrodynamic models are set forth.

2.1 METHODS FOR DETERMINING HYDRODYNAMIC COEFFICIENTS

2.1.1 Theoretical Analysis

For theoretical analysis of vehicle dynamics, the vehicle is modeled as a rigid body moving through a viscous fluid. This analysis can be broken down into several components. Some of these components are well understood; others are not.

The kinematics and dynamics of a rigid body acted upon by arbitrary forces and moments have been well understood since Euler. The problem then is the calculation of the forces and moments due to the fluid. The hydrostatic forces are again well understood. The hydrodynamic forces can be split into two classes: those that would be present in an inviscid fluid and those that are due to the viscosity in the fluid. Inviscid fluid effects may be complex for a body of arbitrary shape, but can be calculated using a modern digital computer of moderate capacity. Added hydrodynamic mass is an important inviscid effect. Most work on seakeeping is based on inviscid flow methods [8]. This is usually a good approximation for the relatively high frequency wave-induced motions of ships at sea.

Viscous fluid dynamics effects are difficult at present to predict accurately and consistently. These effects strongly influence ship maneuvering in calm water. The classical theory of ship maneuvering is based on the differential equations of motion which apply to the irrotational flow past a rigid body in an ideal fluid. To these are added semi-empirical corrections to account for viscous, free-surface and lifting-surface effects. Most theoretical models neglect viscous and free-surface effects, and treat lifting phenomena under the assumptions that the ship hull is slender, and that the lateral motions are small by comparison to the forward velocity [9].

J.N. Newman [9] summarizes the state of the art of theoretical prediction methods as follows:

> "Existing comparisons between theory and experiments are less satisfactory than might be desired. In most cases, the degree of qualitative agreement is reasonable, and the theoretical descriptions are useful in the context of interpolation between sparse experimental and empirical data. But from the quantitative standpoint, differences as large as 50% are common. It is likely that most of these differences are the fault of the theories, rather than experiments.
>
> The principal defects of the theory are overprediction of the force and moment due to the rudder, and underprediction of the force on the hull due to its own lateral motions or external disturbances. Attempts to improve the prediction of rudder effectiveness by semi-empirical corrections have not been sufficiently rewarding. Indeed, it seems likely that the flow at a ship's stern is too complex to describe adequately by any conceivable theory."

Numerical finite-element-style solution of the complete Navier-Stokes equations, which represent both viscid and inviscid effects, shows some promise. At present, results are confined to special cases which do not involve viscous effects [10].

2.1.2 Captive Scale Model Tests [11]

The tests of scale model vehicles can be used to provide some of the data required for the estimation of the parameters required by an accurate hydrodynamic model. This section outlines the capabilities and drawbacks of the commonly used tank testing techniques.

2.1.2.1 Oblique Towing

Oblique towing tests are carried out in order to determine the longitudinal and transverse forces and the yaw moment on the ship as a function of the speed, sideslip angle, rudder angle, and propeller rpm.

Three kinds of tests are performed:

(1) static control surface tests during which forces and moments are measured for zero degree drift angle and several combinations of speed, rpm, and rudder deflection;

(2) static drift angle tests during which force and moment are measured for several combinations of speed and sideslip angle, while the rudder is kept at zero degrees and the rpm correspnds to the full-scale propulsion point; and

(3) cross-coupling tests during which effects of the various sideslip angles on the rudder effectiveness are determined.

During these tests, the torque of the propeller is measured as well.

2.1.2.2 Rotating Arm

The rotating arm technique is used specifically to determine the hydrodynamic derivatives of yawing, but may also be used for the same purpose as the oblique towing tests.

In the rotating arm tests, the model is towed along circular paths at a constant linear speed. The angular velocity is changed by varying the radius of the circle. A dynamometer measures the transverse force and the angular moment acting on the model.

The main drawback of the rotating arm technique is that it cannot be used to determine the angular acceleration derivatives Also, there are some problems associated with its operations, namely:

(1) the model must be accelerated and all the measurements taken in one revolution in order to avoid the interference of the model's wake; and

(2) in order to perform the tests at a small value of the angular velocity, it is necessary to use a high ratio of the radius of the turn to the model length. This frequently requires the use of smaller models, which in turn leads to scale effects.

2.1.2.3 Planar Motion Mechanism [11,12]

The planar motion mechanism (PMM) tests are carried out with the primary purpose of determining the acceleration derivatives (added mass and added moment of inertia coefficients) and some of the cross-coupling derivatives such as the ones involving drift and yaw.

The PMM can be mounted on the carriage of a towing tank. It imparts oscillatory motions to the bow and stern of the model while it is being towed at constant speed. By carefully selecting the phase angle between the bow and stern oscillations, it is possible to establish a motion that is pure yaw, pure sway, or any combination of the two.

During the PMM tests, the propeller rpm is adjusted in accordance with the full-scale propulsion point. The test data, being cyclic, are affected by:

(1) tank resonance -- a function of tank dimensions and test frequency;

(2) free-surface waves generated by a model at the surface -- a function of the speed and test frequency; and

(3) unsteady lift or memory effects.

2.1.2.4 Horizontal Oscillation Techniques

The oscillation technique differs from the PPM in that only one oscillator is used to oscillate the model in yaw about any selected origin while that origin is towed in a straight line along the towing tank.

The motions of the model during the tests are always a combination of rotation and translation. Hence, the force and moment measured during the oscillations are a mixture of static, rotary and acceleration components. In order to determine the rotary and acceleration derivatives, it is necessary to know beforehand the static force and moment derivatives. The forces

and moments are measured for the model oscillated about two different locations of the origin, and the unknown hydrodynamic derivatives are then determined by the solution of a system of simultaneous equations.

The biggest drawback of the oscillator techniques is the possibility of introducing considerable errors in the solution of the simultaneous equations because of the wide difference in magnitude between the individual derivatives. Therefore, the results of the oscillator type of test are not usually considered as accurate as those obtained from the PMM.

All of the tank test methods described above contain several disadvantages. The primary problems are scale effects. In general, the parameters in the hydrodynamic force and moment relations vary as a function of the relevant dimensionless parameters such as Reynolds or Froude. At present, it is impossible to determine these functions exactly. Also, the towing tank walls and bottom modify the flow field around the ship model. The rotating arm technique suffers additionally by requiring a very large facility.

Scale and tank wall effects will be a particular problem when testing captive ship models at very high angles of sideslip. To test a ship model in pure sway motion (i.e. sideslip angle of 90°), the model must be towed in the tank with the model's long axis oriented perpendicular to the long axis of the tank. For any given tank, this will require the use of smaller models than those usually tested in order to avoid tank wall tares.

Reynolds number scale effects will probably be more significant during tank tests conducted in shallow water than in deep water. The influence of the bottom surface of the tank/ocean on the ship's boundary layer accounts for some of the modification of the ship's maneuvering characteristics in shallow water. The scale model boundary layer will probably be significantly different from that of the full size ship, leading

to possible significant difference is hydrodynamic characteristics.

Tank testing methods have another drawback. Namely, the tests do not provide information for complete model structure determination. All of these tests depend upon inducing special motions while restricting others in order to isolate the effects of various stability derivatives or possible nonlinear terms. The experimenter can only estimate the values of parameters relating to the hydrodynamic effects whose existence is suspected *a priori*. For definitive hydrodynamic force model structure determination, another technique, such as free-running reduced-scale model experiments or full-scale trials, is essential.

2.1.3 Full-Scale Vehicle Tests

The effects of tank walls and/or *a priori* model structure misconceptions can be eliminated by using data from full-scale vehicle tests. Scale effects can only be eliminated by using the actual vehicle in full-scale trials. However, full-scale trials present their own set of difficulties. First, the environment in which the vehicle operates is not precisely controlled as is the case with tank tests. Random process disturbances such as those from wave forces and water currents can affect results in ways which are difficult to isolate and quantify.

The data recorded by each of the instruments used on a full-scale vehicle test will be a function of all of the parameters of interest. The direct physical isolation of the effects of individual parameters, the goal of tank test techniques such as oblique towing, is usually not possible. Isolation of the parameters must be done by software.

The role of system identification [13,14] in vehicle dynamic modeling must be defined in the light of the purpose of such modeling and the available techniques for gathering data and

postulating model structure. The unique potential contributions of system identification to ship modeling can be summarized as follows.

2.1.3.1 Validation

Vehicle hydrodynamic models can be determined using tank testing and theoretical analysis. However, complete confidence in the results of these models is not possible until the resulting models can predict the behavior of full-scale, free-running vehicles. It is doubtful that the theoretical or empirical models will yield perfect agreement initially with full-scale trial results. The development of models from full-scale test data using system identification can isolate and quantify the deficiencies of the *a priori* models.

2.1.3.2 Estimation of Unsteady Hydrodynamic Effects

The hydrodynamic forces and moments acting on the vehicles depend on unsteady hydrodynamic effects. These effects are difficult to treat analytically. It is also difficult to measure these effects using tank testing methods due to nonlinearity and tank resonance effects. The detailed quantitative analysis of full-scale data may be essential to an understanding of unsteady hydrodynamic effects. (Some tank test methods have been proposed for the study of this problem [15].)

2.1.3.3 Determination of Model Structure

Perhaps the strongest argument for free-running model tests, and the subsequent processing of data using system identification, is that such tests can give the analyst or experimenter information on phenomena whose presence is not known, or at least only suspected. The significance of

previously neglected phenomena should be revealed by the inability of system identification techniques to match free-running test data using <u>a priori</u> model structures. The determination of a satisfactory model structure with accurate parameters estimates will also require insight into a large range of hydrodynamic phenomena together with data processing techniques able to extract the maximum information from the available data.

Tank tests and theoretical analysis can determine some parameters and a candidate structure of hydrodynamic models. The role of system identification is to process the data from full-scale tests, to validate parameter estimates, and to assess the adequacy of the model structure.

2.2 REQUIREMENTS FOR FULL-SCALE TEST DATA COLLECTION

The estimation and validation of hydrodynamic coefficients from full-scale maneuvering trials requires

- a data-collection system able to record essential elements of the dynamic response of the ship;
- a test plan which includes a sequence of maneuvers which will excite all of the dynamic response variables of the ship;
- the availablity of a ship for testing;
- a system identification algorithm which can estimate the hydrodynamic coefficients from the recorded data;
- correlation of estimated coefficient values with coefficients determined using other methods such as tank tests; and
- off-line validation testing.

The data-collection system must, at a minimum, determine two general categories of information: dynamic response variables and control inputs. Hydrodynamic forces and moments are functions of each of the dynamic response variables. These variables are:

- body-fixed translational velocity components;
- body-fixed translational acceleration components;
- yaw rate; and
- yaw acceleration.

Hydrodynamic forces and moments also depend on the control inputs:

- rudder(s);
- propeller rate(s); and
- auxiliary thrusters.

Additionally, sensors may be required in order to make measurement of special environmental factors, including

- water current;
- wind;
- proximity effects, including passing ship or restricted waterway effects; and
- random seaway.

If water current, wind, or random seaway are significant, then heading must be determined.

Table 2.1 indicates sensors which would be required for hydrodynamic coefficient estimation in the presence of a number of environmental factors. The representative applications sections of this table highlight critical requirements for measurement of specific environmental elements. Wind, for example, affects the maneuvering of almost all ships. But liquified natural gas (LNG) carriers and containerships are particularly sensitive to this factor because of their large cross-sectional area above the water plane.

It is noted that Table 2.1 explicitly contains sensors with ship motion data redundancy. For example, in ideal theoretical conditions, position fix data could be differentiated in time to produce information identical to that obtained from inertial

Table 2.1

Instrumentation Package Sensors/Applications Summary

BASIC PACKAGE
• INERTIAL INSTRUMENTS • DIGITAL COMPUTER • MAGNETIC DATA STORAGE • NAVIGATION FIX • SHIPBOARD SENSOR INTERFACES

ADDITIONAL INSTRUMENTS	ENVIRONMENT						
	CALM WATER	CURRENTS	SHALLOW WATER	RESTRICTED WATERWAY	CLOSE SHIP ENCOUNTERS	SEAWAY	WIND
• RUDDER ANGLE PROP RPM	•	•	•	•	•		
• GYROCOMPASS		•				•	•
• ANEMOMETER							•
• DOPPLER SPEED LOG		•					
• SONAR FATHOMETER			•	•			
• PRECISION RADIO POSITIONING*				•	•		
• WAVE RIDER • WAVE HEIGHT RADAR						•	

REPRESENTATIVE APPLICATIONS	CALM WATER	CURRENTS	SHALLOW WATER	RESTRICTED WATERWAY	CLOSE SHIP ENCOUNTERS	SEAWAY	WIND
LNG	•	•	•	•	•	•	•
VLCC	•	•	•		•	•	
RIVER TOW	•			•			
CONTAINERSHIP	•	•	•	•	•	•	•

* RAYDIST OR SIMILAR

instruments. Differentiation, however, tends to amplify signal noise levels. Practical limitations preclude unlimited application of this procedure. On the other hand, body-fixed components of velocity can be determined using inertial navigation algorithms operating with data from translational accelerometers and radio position fixes. This is an effective procedure with noisy data. A key question for the analysis is which sensors should, in fact, be used for the fundamental translational motion data source in a real marine environment. Section IV covers the evaluation of sensor requirements.

Hydrodynamic model structure and accuracy requirements fundamentally affect the sensor accuracy specifications. Section III discusses candidate model structures and the relation of hydrodynamic coefficient accuracy to maneuver simulation fidelity.

III. HYDRODYNAMIC MODELS: STRUCTURES AND ACCURACY REQUIREMENTS

A maneuvering simulation model of a ship [9] is a differential equation which models both dynamic (force, mass, acceleration relationships) and kinematics (geometry, velocity, position relationships). The crucial element in this simulation is the hydrodynamic model. This computes forces and moments on the ship given the ship's velocity and angular rate with respect to the water. The hydrodynamic model is the least understood portion of the overall ship simulation model. This section addresses two important issues regarding the hydrodynamic model:

(1) The structure of a hydrodynamic model is the mathematical form of the expression relating forces and moments to ship motion. At least two somewhat different forms are commonly in use in the ship simulation community [12,16]. Section 3.1 discusses the minimum common requirements which any structure must satisfy. It also proposes an alternative structure which may solve some of the difficulties encountered by the present models. This alternative structure makes use of spline functions [17].

(2) No specifications exist for accuracy of hydrodynamic models. Systems identification is a statistical estimation process. Data are noisy, indirect measurements of the hydrodynamic model. The accuracy of the estimated model depends on the accuracy of the measurements (i.e. sensors). It is necessary to have some idea of model accuracy requirements in order to specify sensor type and accuracy requirements. Section 3.2 determines the sensitivity of three definitive maneuvering characteristics (stability, overshoot angle, and turning radius) to small changes in the parameters which define the hydrodynamic model. These sensitivities are then used to determine acceptable levels of uncertainty in model parameters.

These levels are based on prediction error bounds for maneuvering characteristics [11].

3.1 MANEUVERING SIMULATION MODEL STRUCTURES

3.1.1 Fundamental Requirements

Ship motion simulation models the ship as a rigid body acted upon by hydrodynamic and hydrostatic forces. Seakeeping simulations represent all six degrees of freedom of the rigid body (Figure 3.1). Maneuvering simulations neglect three of the degrees of freedom (roll, pitch and heave). The resulting model represents the yaw, sway, and surge degrees of freedom (u, v, and r) of the ship moving in the horizontal plane. The equations of motion of the ship are:

$$m[\dot{u} - vr] = F_x \text{ (surge equation)}$$

$$m[\dot{v} + ur] = F_y \text{ (sway equation)}$$

$$I_z\dot{r} = M_z \text{ (yaw equation)}$$

F_x, F_y, and M_z are the two forces and single moment acting on the ship. These three terms are due to hydrodynamic and aerodynamic forces and are expressed in terms of dimensionless terms called total hydrodynamic or total aerodynamic coefficients.

$$F_x = \tfrac{1}{2}\rho_h U_h^2 \ell^2 C_x^h + \tfrac{1}{2}\rho_A U_A^2 \ell^2 C_x^A$$

$$F_y = \tfrac{1}{2}\rho_h U_h^2 \ell^2 C_y^h + \tfrac{1}{2}\rho_A U_A^2 \ell^2 C_y^A$$

$$M_z = \tfrac{1}{2}\rho_h U_h^2 \ell^3 C_n^h + \tfrac{1}{2}\rho_A U_A^2 \ell^3 C_n^A$$

Aerodynamic coefficients ("A" superscripts) will not be treated in detail here. Similarity analysis shows that the total hydrodynamic coefficients ("h" superscripts) depend on the following dimensionless quantities.

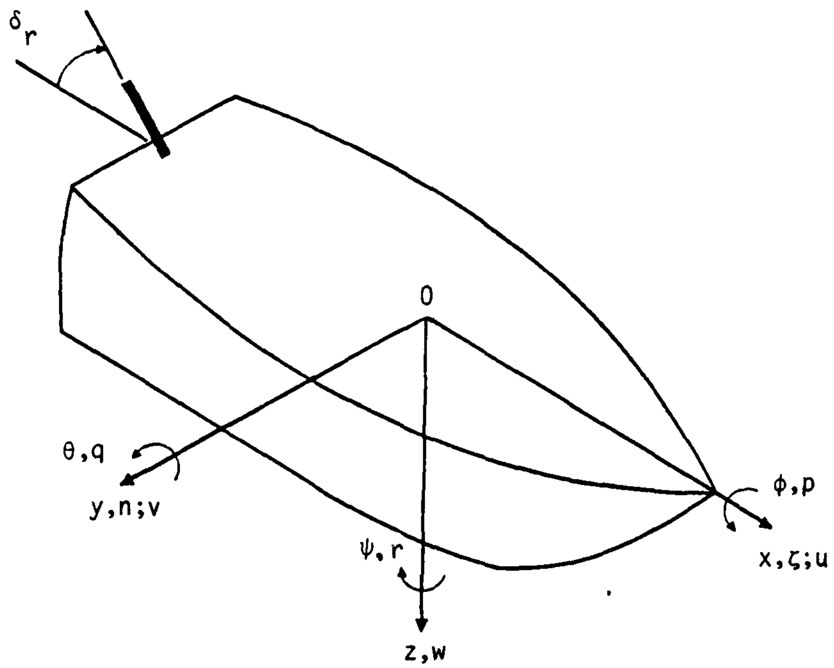

Figure 3.1(a) Ship Coordinate System — Body Axes with Origin at Center of Gravity

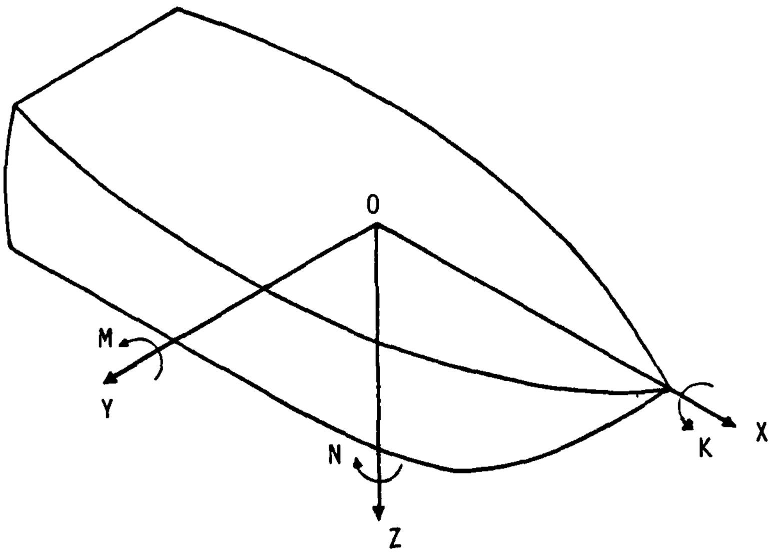

Figure 3.1(b) Ship Coordinate System — Body Axes Forces and Moments

$$\beta = \tan^{-1}(v_h/U_h) \cong v_h/U_h$$

$$r' = r_h \ell / U_h$$

$$\eta = U_c/U_h$$

δ = rudder angle (possibly multiple rudders)

$$\dot{v}' = \dot{v}_h \ell / U_h^2$$

$$\dot{r}' = \dot{r}_h \ell^2 / U_h^2$$

$Re = \rho U_h \ell / \mu$ (Reynolds number)

$Fr = U_h / \sqrt{g\ell}$ (Froude number)

Determination of a hydrodynamic model requires the determination of the function

$$C_x(\beta, r', \delta, \eta, \dot{v}', \dot{r}', Re, Fr)$$

and similarly for C_y and M_z. The model structure determination problem is that of finding a mathematical form which can represent the nonlinear functions C_x, C_y, and C_n. The parameter estimation problem is that of determining the numerical values of parameters in the model.

3.1.2 Representation of Hydrodynamics

3.1.2.1 Commonly Used Model Structures

Table 3.1 lists two commonly used structures for representing the three total coefficients. The first form [16] (used by the CAORF simulator) uses a third-degree Taylor series expanded to represent the effects of β and r'. Symmetry indicates that odd-degree terms must appear in the yaw moment and sway force equations while even-degree terms must appear in the surge force equations. The second form uses a "square-absolute"

Table 3.1

Alternative Forms for Hydrodynamic Coefficients
(Lateral Force Equation Illustrated)

SQUARE ABSOLUTE FORM:

$$C_y = Y_* + Y_v(v) + Y_r(r') + K_r(n)\,[Y_\delta(\delta) + Y_{\delta|\delta|}\,\delta|\delta|]$$

$$+ Y_{v|v|}(v')|v'| + Y_{r|r|}(r')\,|r'| + Y_{v|r|}(v')|r'|$$

$$+ Y_{r|v|}(r')\,|v'|$$

CUBIC FORM:

$$C_y = Y_* + Y_v(v') + Y_r(r') + K_r(n)[Y_\delta(\delta) + Y_{\delta\delta\delta}(\delta)^3]$$

$$Y_{vvv}(v')^3 + Y_{rrr}(r')^3 + Y_{vrr}(v')(r')^2 + Y_{rvv}(r')(v')^2$$

[5,12] representation for the odd functions in the yaw and sway equations. Some theoretical considerations indicate that the nonlinear forces and moments may be proportional to the square of yaw rate and of lateral velocity rather than to terms cubic in these quantities. The square-absolute terms then are probably, but not necessarily, a more accurate representation of the real world.

The fixed parameters appearing in Table 3.1, Y_*, Y_v, etc. are commonly called the hydrodynamic coefficients of the model.

For simulation of ship or river tow motion at moderate angles of sideslip ($\beta < 20°$), the square-absolute forms and the cubic forms are very nearly equivalent. Both forms can represent very similar maneuvering characteristics. The square-absolute form is used in the simulation studies performed in the sensor requirements section (Section IV) because coefficients for this form of model are available from tow tank test results [5].

The propulsion terms [5] X_p, Y_p, N_p are represented as a quadratic function of the propulsion ratio:

$$X_p = X_* + X_\eta \eta + X_{\eta\eta} \eta\eta$$

and similarly for Y_p and N_p.

The interaction of propulsion with rudder is complex and is difficult to model. If a rudder is located in the race of a propeller, the effectiveness of the rudder is increased when the propulsion ratio is increased above 1.0. The effectiveness is decreased when the propulsion ratio is decreased below 1.0. Additionally, the rudder effects are nonlinear at constant propulsion ratio. This is because the rudder stalls at high local angles of attack ($\alpha_\ell < 15°$). The commonly used rudder lateral force model is [5,16]

$$\begin{array}{l}\text{rudder lateral} \\ \text{force}\end{array} = f_\eta(\eta)[Y_\delta \delta + Y_{\delta\delta\delta}\, \delta^3]$$

f_η is the rudder force multiplying factor. This can be represented as a quadratic polynomial in η [5]

$$f_\eta(\eta) = f_\delta + f_{\delta\eta}\eta + f_{\delta\eta\eta}\eta^2$$

An alternative representation uses an exponential function [16]

$$f_\eta(\eta) = K_1[1 + K_2(1 - 1/\eta)^{3/2}]$$

with K_1 chosen to make $f_\eta = 1.0$ for $\eta = 1.0$.

3.1.2.2 Spline Model Structures

Spline functions [17] have found widespread use in many areas of mathematical modeling. Their use is recommended here for representing the hydrodynamic characteristics of the river tow over its complete operational envelope. Spline functions are piecewise polynomial (usually cubic) functions satisfying continuity conditions between regions. The spline representation for river tow hydrodynamic models would be useful for modeling those physical processes which are so complex that it is difficult to parameterize the effects of various forces from a priori analysis. Three prime candidates for spline modeling would be

- rudder force multiplying factors [16] as a function of propulsion ratio η;
- yaw moment as a function of sideslip angle β over a region from $\beta = -\pi$ radians (backing directly astern) to $\beta = -\pi/2$ radians (moving directly athwartships) to $\beta = 0$ radians (moving directly forward); and
- side force over the same region of β.

Symmetry indicates that yaw moment and side force for $\beta > 0$ could be very nearly the same as that for $\beta < 0$ except for a sign change.

Brevity precludes a complete treatment of spline function modeling of vessel hydrodynamics here. One example, however, should illustrate the general method. The rudder force

multiplying factor, f_η, represents the change in rudder effectiveness with respect to change in propulsion coefficient η. Figure 3.2 illustrates a spline function model of f_η. The model uses eight parameters to define the $f(\eta)$ function over three regions. The variable parameters are the four knot locations and $f(\eta)$ evaluated at the η values corresponding to the knot locations.

3.2 COEFFICIENT ACCURACY REQUIREMENTS

This section derives relationships between hydrodynamic coefficient accuracy and accuracy of simulation of certain definitive maneuvering characteristics of ships. This allows the specification of allowable coefficient estimation errors in terms of allowable error in simulation of these characteristics.

3.2.1 Definitive Maneuvering Characteristics

In general, any ocean-going or inland-waterway vessel needs to be able to perform the maneuvering tasks listed in Table 3.2 [14]. Table 3.2 also lists quantitative measures of these tasks which can be reproduced with a maneuvering simulation. The ship can execute certain definitive maneuvers which yield direct information about the quantitative measures listed. (The spiral maneuver gives somewhat indirect information about the stability indices. The presence of a hysteresis loop in the spiral test result indicates that some unstable behavior of the ship exists. A loop with a wider width indicates an unstable index of larger magnitude.)

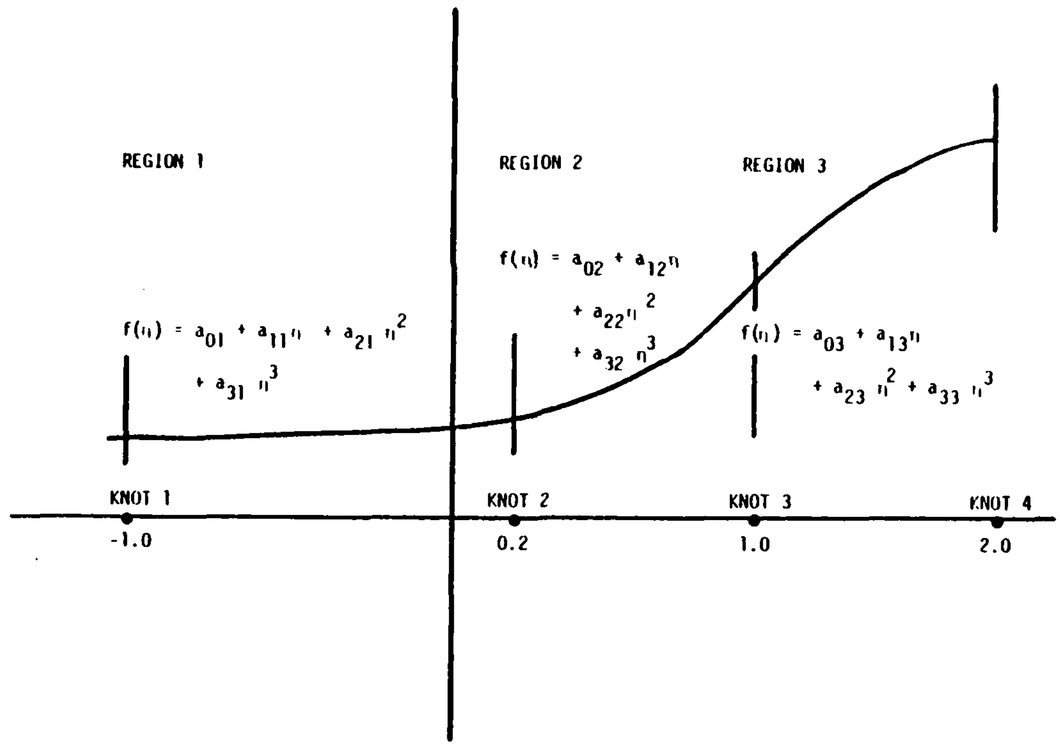

Figure 3.2 Spline Function Model of Rudder Force Multiplying Factor

Table 3.2
Minimum Maneuvering Tasks

MANEUVERING TASK		QUANTITATIVE MEASURES	DEFINITIVE MANEUVER
Keep a Course		Stability Indices: σ_1, σ_2 [21]	Spiral
Change Course	Execute a Turn	Turning Radius R_t	Turning Circle
	Check a Turn	Overshoot Angle ψ_o	Zig-Zag
Stop		Stopping Distance X_s	Crash Stop

3.2.2 Sensitivity of Definitive Maneuvering Characteristics to Small Changes in Hydrodynamic Coefficients

It is of interest to determine the sensitivity of the quantitative measure of the simulation model to small changes in the hydrodynamic coefficients. The sensitivity gives information on the relative importance of the various hydrodynamic coefficients to the response of the simulation model during specific maneuvers. This information tells which coefficients must be known most accurately to simulate the given maneuvers and thus aids in the planning of programs of coefficient determination.

Sensitivity is defined as follows. Let Φ be a quantitative measure of a maneuvering task. Let θ be a hydrodynamic coefficient. Then the sensitivity of Φ with respect to θ is represented as Φ_θ.

$$\Phi_\theta = \partial\phi/\partial\theta$$

A practical way to approximate this is

$$\Phi_\theta \cong \frac{\phi[\theta(1+\Delta) - \phi[\theta(1-\Delta)]}{2\varepsilon}$$

The quantities $\phi[\theta(1+\Delta)]$ and $\phi[\theta(1-\Delta)]$ can be evaluated using the digital simulation. An effective choice for ε when evaluating partial derivatives using finite difference approximation is

$$\Delta = \sqrt{\varepsilon}$$

where ε is the computer machine precision.

A dimensionless, normalized sensitivity may yield somewhat more immediate insight than the raw sensitivity itself. The normalized sensitivity is

$$\overline{\Phi}_\theta = [\partial\phi/\partial\theta] \; |\theta/\phi|$$

Table 3.3 lists the sensitivity of the stability indices of the river tow boat to changes in the eight hydrodynamic coefficients which affect the indices. For each stability index, the coefficients are listed in the order of their significance to that index, with a larger sensitivity indicating a greater

Table 3.3

River Tow Stability Index Sensitivity

σ_1 Sensitivity (Nominal $\sigma_1 = -0.49$)		σ_2 Sensitivity (Nominal $\sigma_2 = -2.4$)	
θ	$[\partial\sigma_1/\partial\theta]\,\lvert\theta\sigma_1\rvert$	θ	$[\partial\sigma_2/\partial\theta]\,\lvert\theta/\sigma_2\rvert$
Y_v	+1.4	N_r	+0.86
N_r	+0.57	$N_{\dot{r}}$	-0.31
N_v	-0.53	N_v	+0.10
Y_r	-0.34	$N_{\dot{v}}$	-0.071
$Y_{\dot{v}}$	-0.33	Y_r	+0.014
$N_{\dot{v}}$	+0.074	$Y_{\dot{v}}$	+0.014
$N_{\dot{r}}$	-0.041	Y_v	-0.012
$Y_{\dot{r}}$	+0.0044	$Y_{\dot{r}}$	-0.0015

significance. The most significant coefficients appear to be Y_v and N_r. The least significant is $Y_{\dot{r}}$. The stability indices and their sensitivities do not depend on the forward speed of the tow boat given the structure of the model used [5]. They do depend on the loading condition and on the specific tow configuration tested. Nonlinear coefficients and control coefficients, which model the effects of rudder and propeller, also have no effect on the stability indices.

Table 3.4 lists the sensitivity of the river tow's steady-state radius of turn to changes in 27 of the hydrodynamic coefficients modeling the tow. As is the case with Table 3.3, the coefficients are listed in order of their significance. Table 3.4 includes two columns. The first column lists normalized sensitivities for nonzero hydrodynamic coefficients. The second column lists sensitivities for coefficients having a zero nominal value. Note that the steady-state radius of turn does not depend on hydrodynamic added-mass.

Table 3.5 lists the sensitivity of the river tow's overshoot angle to changes in the same 27 hydrodynamic coefficients and to four hydrodynamic added-mass coefficients.

The following general conclusions may be drawn from Tables 3.3 through 3.5:

(1) The rudder effectiveness coefficient N_δ is the coefficient most significant to both turning radius and overshoot angle.

(2) Longitudinal force coefficients (f, e, $X_{\delta\delta}$) have significant effects on lateral maneuvering characteristics (turning radius, overshoot angle). This is probably because changes in forward speed significantly affect the hydrodynamic pressure, which multiplies all coefficients in the lateral equations (yaw moment and side force).

(3) Linear coefficients are not uniformly more significant than nonlinear coefficients.

Table 3.4

River Tow Turn Radius Sensitivity

NORMALIZED SENSITIVITIES	
θ	$[\partial T_r/\partial\theta](\theta/T_r)$
N_{δ}	+0.78
f	-0.58
N_r	+0.37
e	-0.33
N_{rn}	+0.21
$N_{r\|n\|}$	+0.21
N_{vr}	+0.20
$X_{\delta\delta}$	-0.15
$N_{v\|v\|}$	-0.11
d	-0.089
N_v	+0.085
N_{vn}	-0.61
X_{vr}	-0.046
Y_{δ}	-0.024
$Y_{v\|v\|}$	0.019
Y_v	0.011
Y_r	0.0097
$Y_{v\|r\|}$	0.0069
$Y_{r\|n\|}$	0.0028
$Y_{r\|r\|}$	-0.0014
Y_{vn}	0.0008
$X_{\dot{u}}$	0.0
$Y_{\dot{v}}$	0.0
$Y_{\dot{r}}$	0.0
$N_{\dot{v}}$	0.0
$N_{\dot{r}}$	0.0

PARTIALLY NORMALIZED	
θ	$[\partial T_r/\partial\theta](1/T_r)$
N*	-5.7
Y*	0.32
$N_{v\|v\|n}$	0.22
$X_{v\|v\|n}$	0.041
$X_{v\|v\|}$	0.040
$Y_{v\|v\|n}$	-0.0034

Table 3.5

River Tow 20/20 Z Maneuver Angular Overshoot Sensitivity

NORMALIZED SENSITIVITIES		PARTIALLY NORMALIZED	
θ	$[\partial\psi_o/\partial\theta]\,\theta/\psi_o$	θ	$[\partial\psi_o/\partial\theta]\,1/\psi_o$
N_δ	1.7	Y^*	2.4
$Y_{\dot v}$	1.6	$N_{v\|v\|\eta}$	-0.021
Y_δ	1.1	X_{vv}	0.0048
$N_{r\|r\|}$	0.81	$Y_{v\|v\|\eta}$	0.00044
$X_{\delta\delta}$	0.80	$X_{vv\eta}$	-0.00040
e	0.72		
f	0.57		
N_r	-0.45		
N_v	0.42		
$N_{v\|r\|}$	-0.35		
$N_{v\|v\|}$	0.16		
$N_{\dot v}$	0.13		
$Y_{\dot v}$	-0.12		
d	0.11		
$N_{\dot r}$	0.091		
$Y_{v\|v\|}$	-0.064		
$N_{r\eta}$	-0.064		
Y_r	+0.032		
$Y_{v\|r\|}$	-0.024		
$N_{v\eta}$	-0.017		
X_{vr}	-0.0078		
$Y_{r\|r\|}$	0.0059		
$Y_{\dot r}$	0.0025		
$X_{\dot u}$	0.001		
$Y_{v\eta}$	-0.00044		

(4) Stability depends only on the eight coefficients listed under Table 3.3. Of these, virtual hydrodynamic mass coefficients are less significant than the other four coefficients.

(5) The most significant effect of virtual mass is on the angular overshoot.

IV. DETERMINATION OF SENSOR ACCURACY REQUIREMENTS

This section uses the functional requirements presented in Chapter II with specialized design software to develop the analytic specification for sensor systems. Seven systems are analyzed regarding their suitability for data collection during river tow trials. The systems include one that uses a highly accurate navigation system based on inertial sensors aided by Loran-C position updates. Such systems are presently under study by MARAD. The other systems make use of less complex sensor components.

4.1 OUTLINE OF METHOD OF APPROACH

The accuracy of hydrodynamic coefficients estimated using data from maneuvering tests depends on several factors

- the class of vessel executing the maneuvers;
- the number, type, and duration of maneuvers executed;
- environmental disturbances such as water currents;
- types of sensors employed (e.g. accelerometers, angular rate gyroscopes, Doppler sonars, radio position fixes, or combinations of these elements);
- intrinsic accuracy (e.g. fundamental random noise levels) of sensors;
- calibration accuracy (e.g. bias errors) of sensors; and
- the estimation algorithm used to process data.

Figure 4.1 illustrates a flowchart for the analytical evaluation of sensor type and accuracy requirements. The method uses simulation and sensitivity calculations to determine expected coefficient estimation accuracy results for a given set of sensors, test maneuvers, and for a given ship being tested.

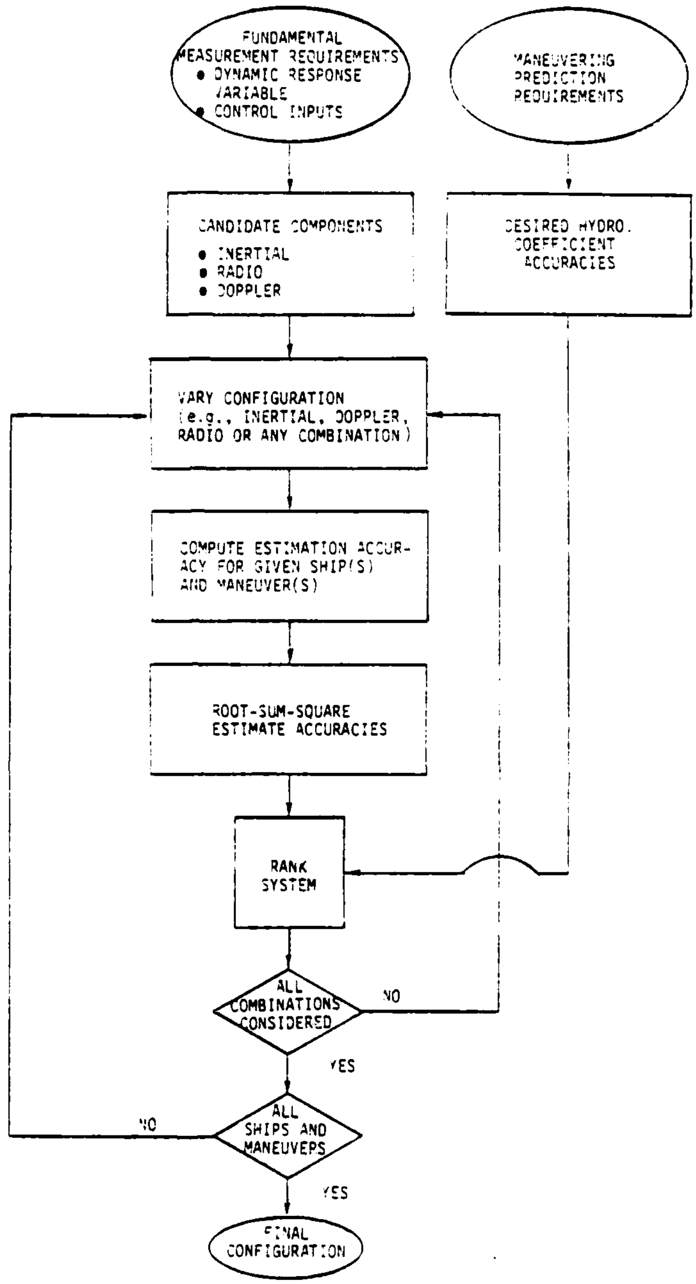

Figure 4.1 Analytical Evolution of Requirements

Figure 4.2 details the accuracy estimation process for systems which may include inertial navigation sensors. The complete process requires simulation of the inertial measurement alignment process (Section 4.2) to determine calibrated acceleration and angular rate accuracies. This is followed by simulation of the vessel test maneuver to determine hydrodynamic coefficient estimation accuracies. If the simulated instrument system does not include an inertial navigation system, then the procedure of Figure 4.2 is used, omitting the alignment simulation.

The accuracy of hydrodynamic coefficient estimation depends on the specific maneuver used to generate data. Figure 4.3 gives plots of dynamic response variables during a simulated modified zig-zag maneuver of a river tow. The simulation model is that of Ref. 5.

For this study, the complete procedure of Figure 4.1 is amended as follows:

- Only one vessel, an inland waterway barge/tow flotilla, is studied by simulation, as opposed to "ALL SHIPS" as indicated. This is primarily because immediate USCG requirements are for the modeling of these river tows.

- The study determines the utility of one typical test maneuver for the identification of a representative set of hydrodynamic coefficients.

Seveal critical considerations underlie the analytic study.

(1) The quality of possibly required inertial instruments is critical because of the wide range of accuracies available and because of the cost of the highly accurate instruments.

(2) Dual-axis Doppler sonar provides a useful direct measurement of the velocity of the ship with respect to the surrounding water or with respect to the bottom. However, river tows will rarely have such Doppler sonar transducers as standard equipment. Doppler sonar transducers must be installed on the bottom of the vessel's hull in a sea chest. The time and expense required to install the complete sensor system increases greatly

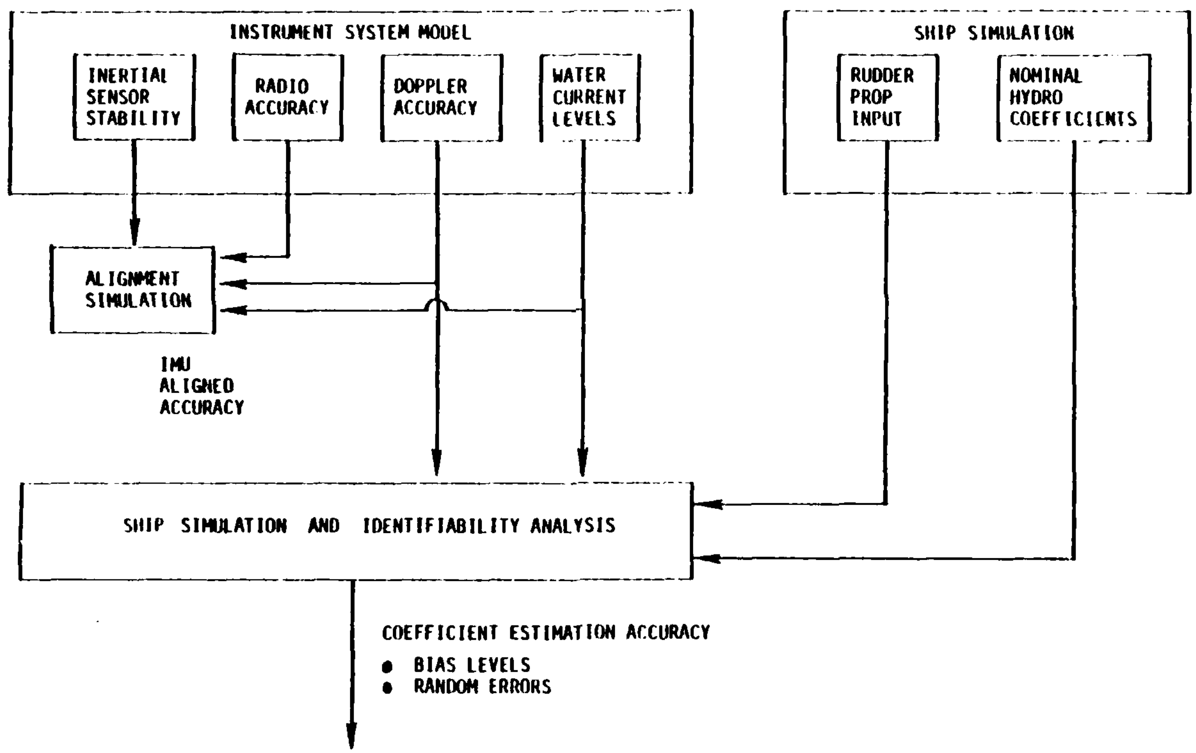

Figure 4.2 Detail of "Compute Estimation Accuracy for Given Ship(s) and Maneuver(s)"

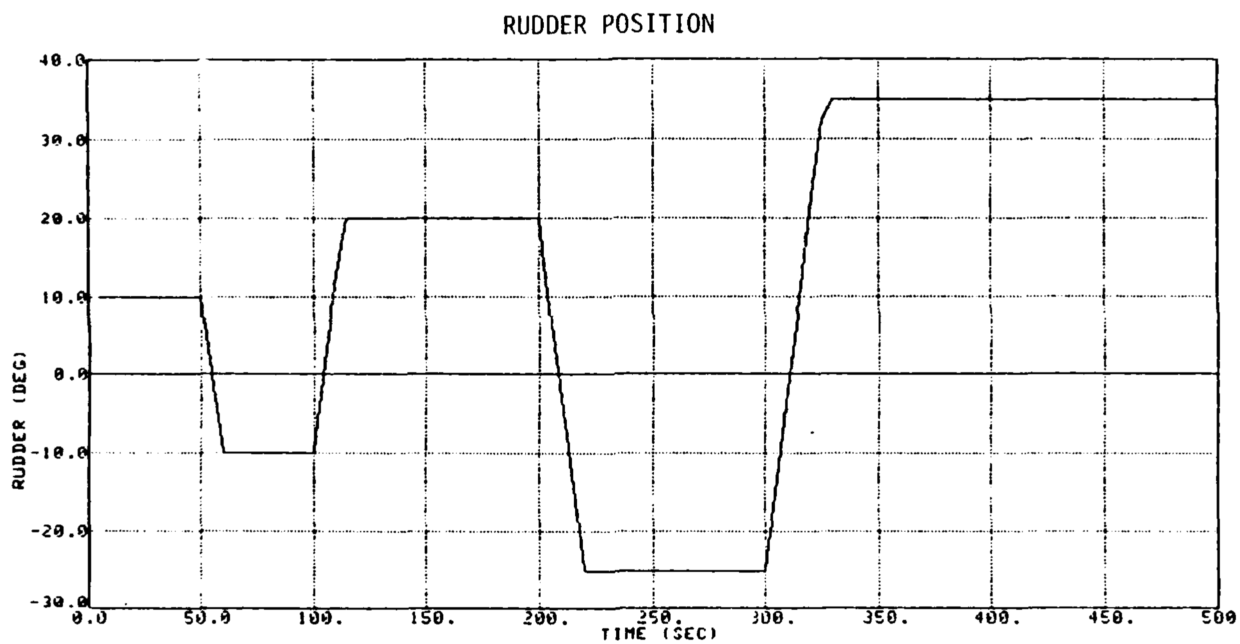

Figure 4.3a Rudder Position

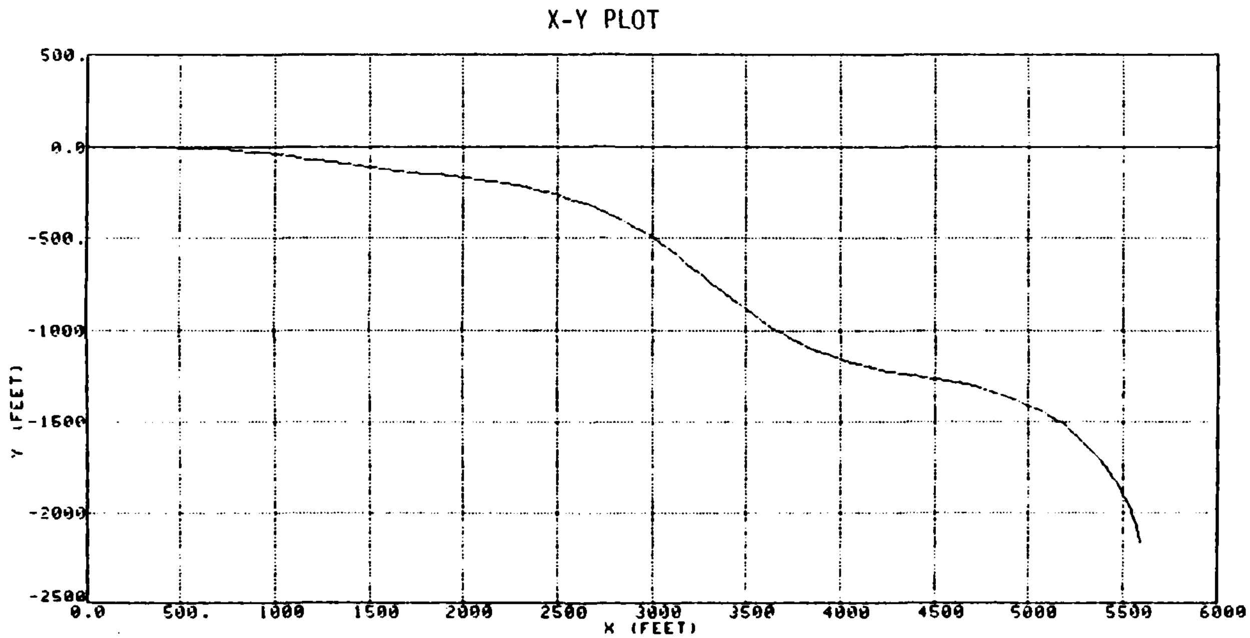

Figure 4.3b Position (X-Y) Plot for River Tow Response to Rudder Input of Figure 4.3a (9 Kt Initial Speed)

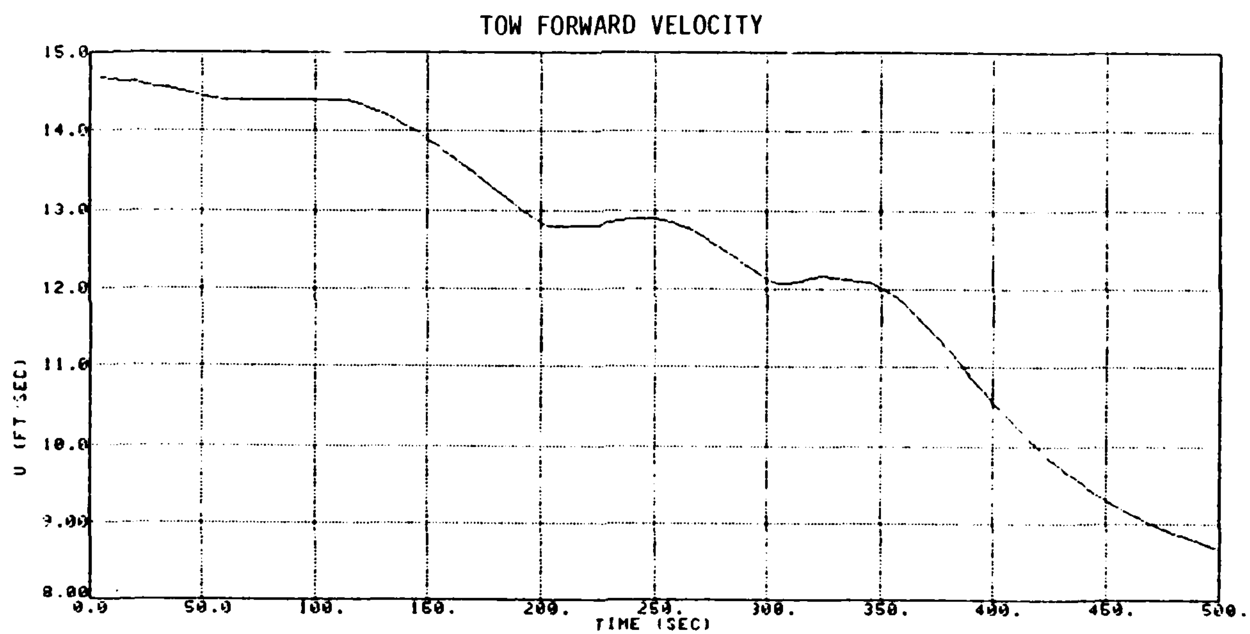

Figure 4.3c Forward Velocity for Piver Tow Response to Rudder Input of Figure 4.2a (9 Kt Initial Speed)

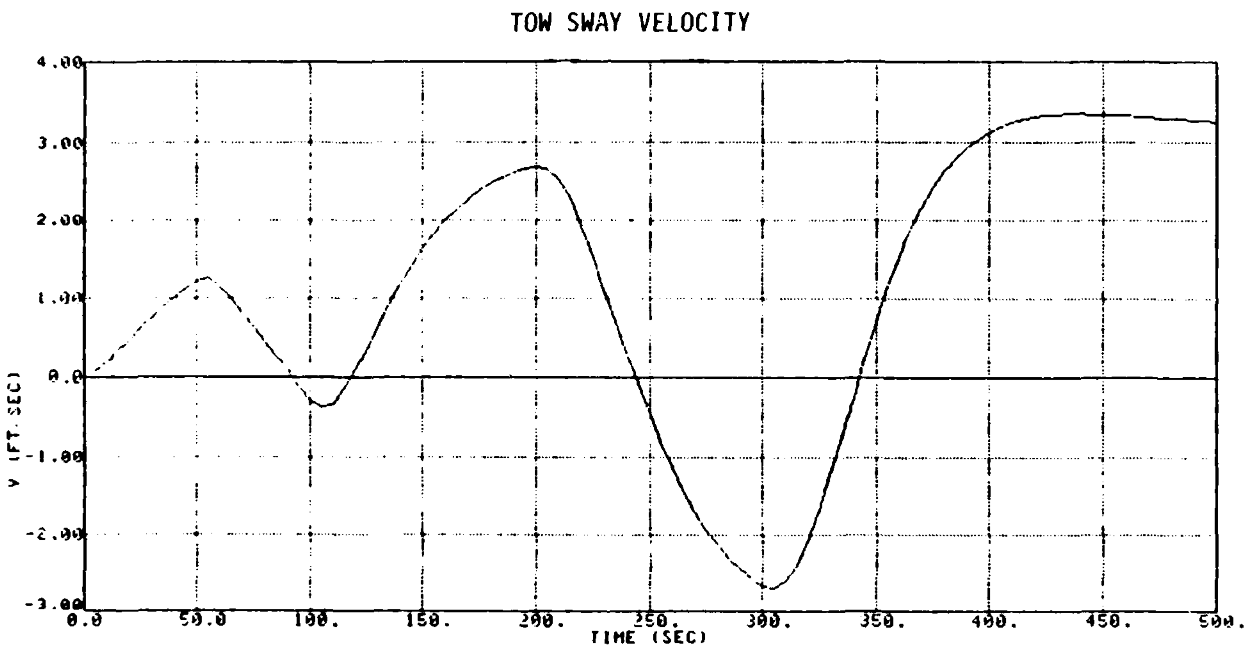

Figure 4.3d Sway Velocity for River Tow Response to Rudder Input of Figure 4.2a (9 Kt Initial Speed)

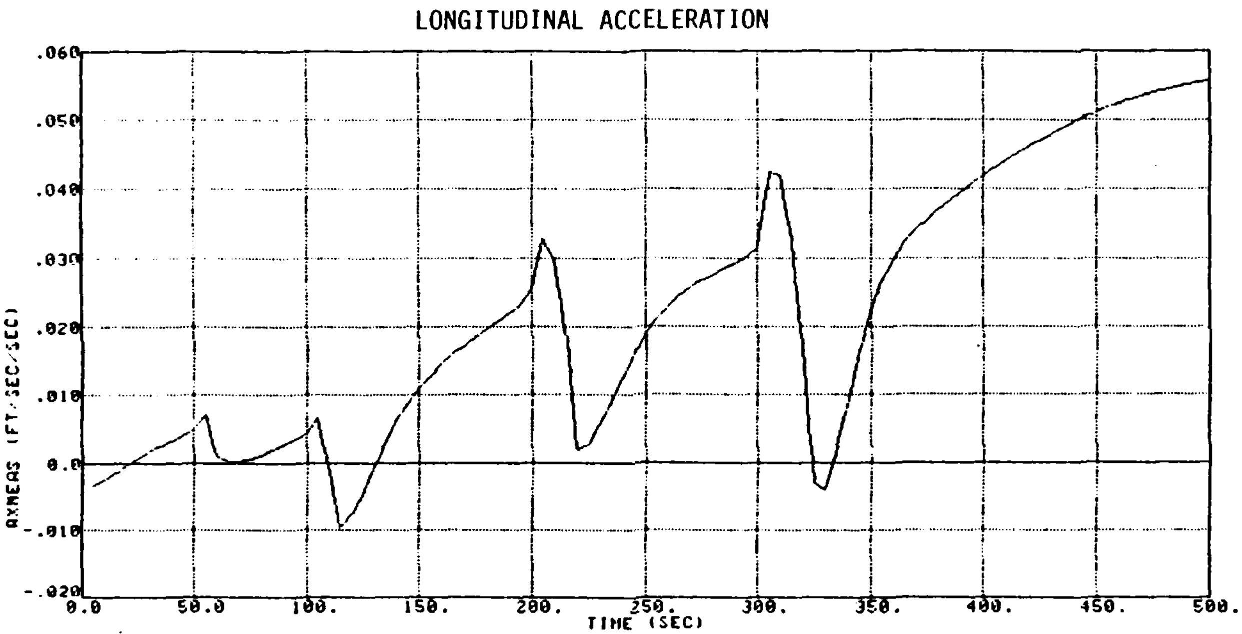

Figure 4.3e Longitudinal Accelerometer Output for River Tow Response to to Rudder Input of Figure 4.2a (9 Kt Initial Speed)

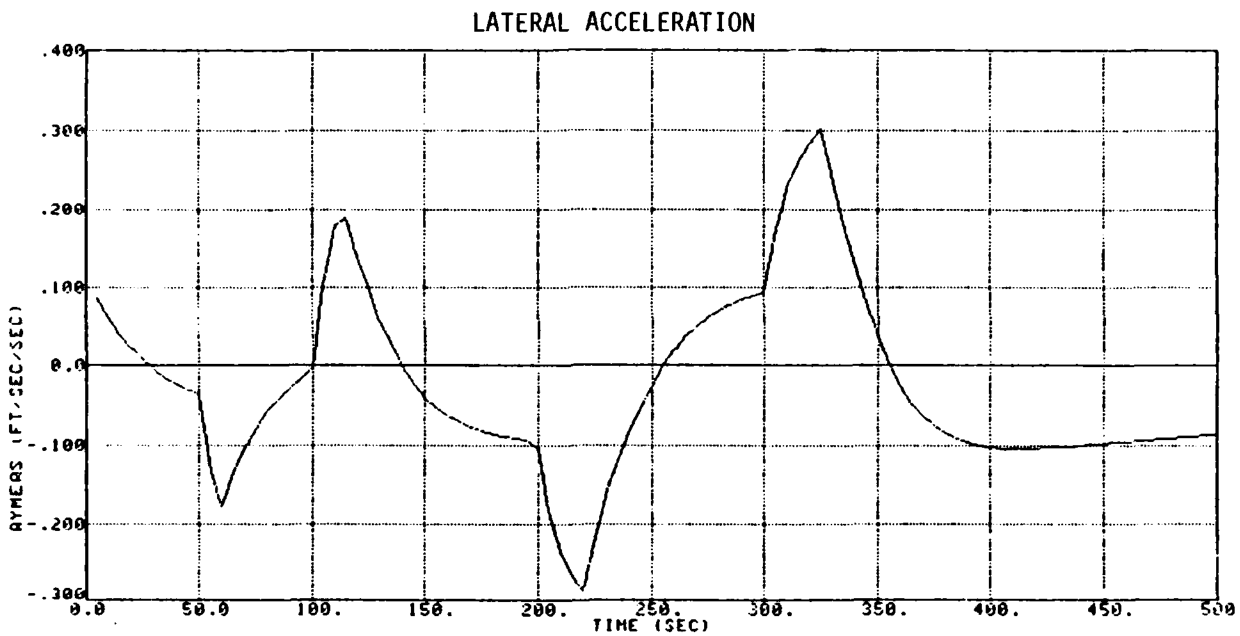

Figure 4.3f Lateral Accelerometer Output for River Tow Response to to Rudder Input of Figure 4.2a (9 Kt Initial Speed)

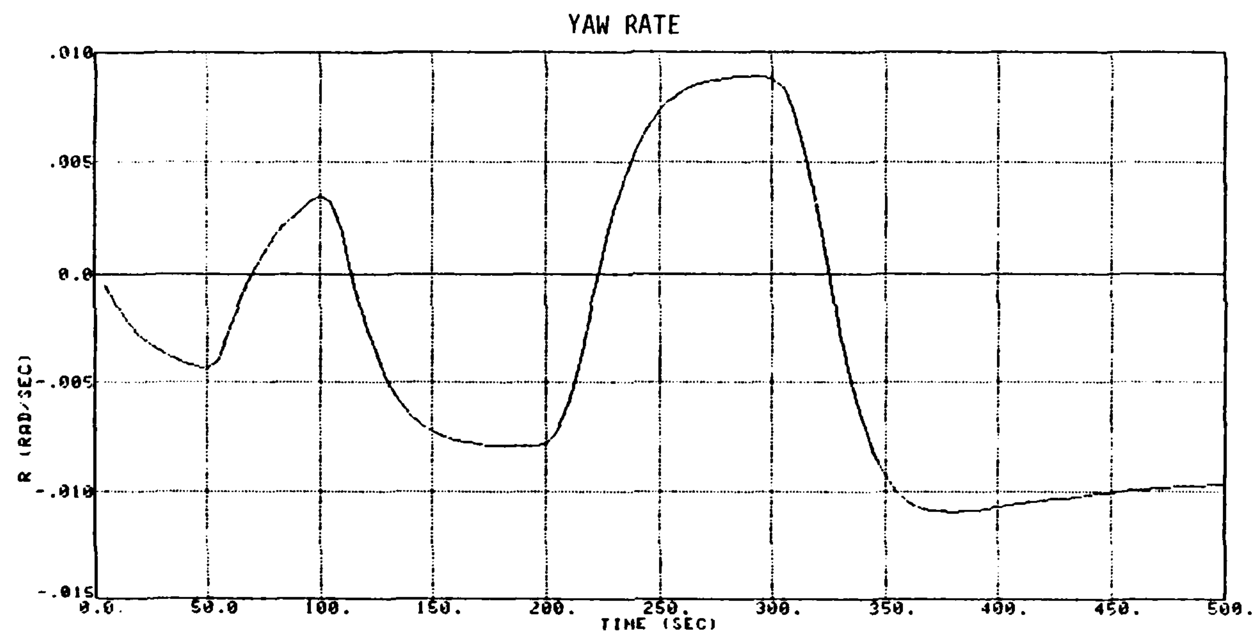

Figure 4.3g Yaw Rate for River Tow Response to Rudder Input of Figure 4.2a (9 Kt Initial Speed)

if a sea chest for a Doppler sonar log must be modified or installed in the vessel's hull.

(3) Radio position and/or Doppler sonar is required in order to align (calibrate) inertial sensors accurately. Radio navigation networks of moderate accuracy, such as Loran-C, are available at most potential maneuvering test sites. The only hardware requirement for the use of such a navigation system is the use of a radio position fix receiver and antenna. More accurate radio position fixing, using a system such as Raydist, will require the deployment of special shore-based transponder stations during the execution of the test maneuvers. This requirement would increase the cost of each test and would possibly preclude the use of some ships which would otherwise be available.

(4) All sensor outputs, as well as several intermediate quantities, must be sampled continually during each test maneuver. A single storage element (tape, disc, or cartridge) should be able to record all of the data during each complete maneuver. The number of bits of data storage required is a function of the number of sensors, the duration of each maneuver, and the sampling rate.

(5) Some configurations of sensors which do not measure all dynamic response variables directly are feasible candidates (at least in theory). Taking precision radio position fixes at the bow and at the stern of the vessel gives information which allows implicit derivation of the fundamental motion quantities such as yaw rate, sideslip angle, forward speed, and accelerations. This configuration of sensors has the potential of being more cost effective than those which make more complete measurements. However, the hydrodynamic coefficients estimated using such a system will have a higher variance than those estimated using a more complete sensor set.

The remainder of Section IV covers the following topics. Section 4.2 defines the sensor type (Doppler sonar or radio

position fix) and accuracy requirements for alignment of an inertial reference system. Section 4.3 defines the hydrodynamic coefficient estimation accuracy attainable using several candidate sensor systems. These results include the effects of degradation of estimation accuracy by water currents. Finally, Section 4.4 draws conclusions about the relative utility of the candidate sensor systems.

4.2 SIMULATION OF AN INERTIAL MEASUREMENT UNIT (IMU)

The complete IMU uses three orthogonally oriented accelerometers and three orthogonally oriented angular rate gyroscopes to measure acceleration and rotation in three-dimensional space. The six sensors must be calibrated continually before and during the maneuvering tests in order to achieve the most accurate estimates of the histories of the dynamic response variables.

Alignment of an IMU is a statistical estimation process. Alignment requires the estimation of the following alignment states:

- IMU attitude with respect to gravitational vertical (equivalent to accelerometer bias level);
- IMU inertial velocity; and
- angular rate gyro bias levels.

IMU alignment is carried out in the following manner. The on-board processor predicts, in real time, IMU position and velocity by integrating translational accelerations and angular rates as measured by the IMU. The processor compares these predictions with independent position and/or velocity measurements. Estimates of the alignment states are updated using the compared differences between the predicted and measured positions and/or velocities.

For the river tow, radio position fixing equipment provides independent position measurements. Doppler sonar can provide

velocity measurements with respect to the bottom in water shallower than 700 ft and can provide velocity with respect to the water. These independent measurements are taken at approximately a two-second sampling period.

The following critical questions must be answered regarding IMU alignment:

- How accurately can the angular rate gyros and the accelerometers be aligned using readily available radio navigation systems such as Loran-C?

- How long will alignment take? Typical IMU alignment times are in the neighborhood of one hour. Significantly longer times might adversely affect the test schedule.

- How sensitive is the alignment to assumed measurement noise levels?

Figure 4.4 gives plots of accelerometer and rate gyro bias estimation accuracy during three alignment simulations. The independent measurements used during these three simulations are:

- Loran-C position fixing only;

- Doppler velocity measurements only; and

- both Loran-C and Doppler measurements.

Nominal measurement noise levels used in the simulation are given by Table 4.3.

The plots of estimation accuracies of Figure 4.4 indicate that estimation accuracies have settled into steady state after about 1200 seconds of alignment. Table 4.4 gives gyro bias (σ_{gyro}) and accelerometer bias (σ_{AX}) estimation accuracy after 20 minutes of alignment. These two error levels directly affect the calculation of hydrodynamic coefficient estimation accuracies summarized in Section 4.4. The table gives results for systems using the nominal measurement noise levels of Table 4.3 as well as for five off-nominal conditions. The following conclusions can be drawn from the results presented in Table 4.4.

(1) If only Loran-C is available as an independent measurement, then both rate gyro and accelerometer alignment

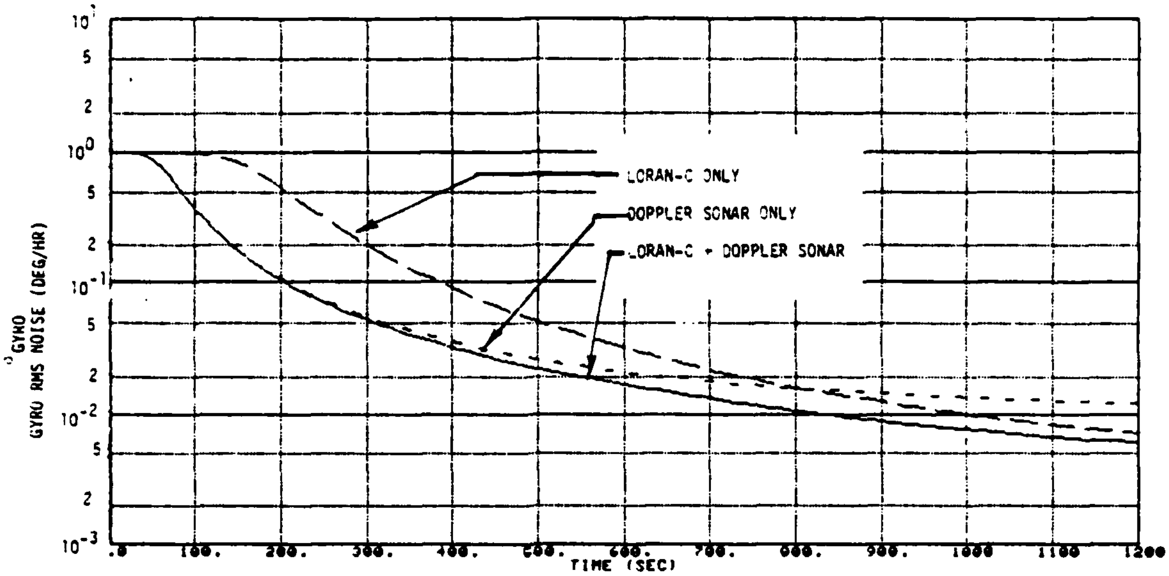

Figure 4.4a Rate Gyro Accuracy, σ_{gyro}
(Nominal Noise Levels of Sensors for Alignment Data)

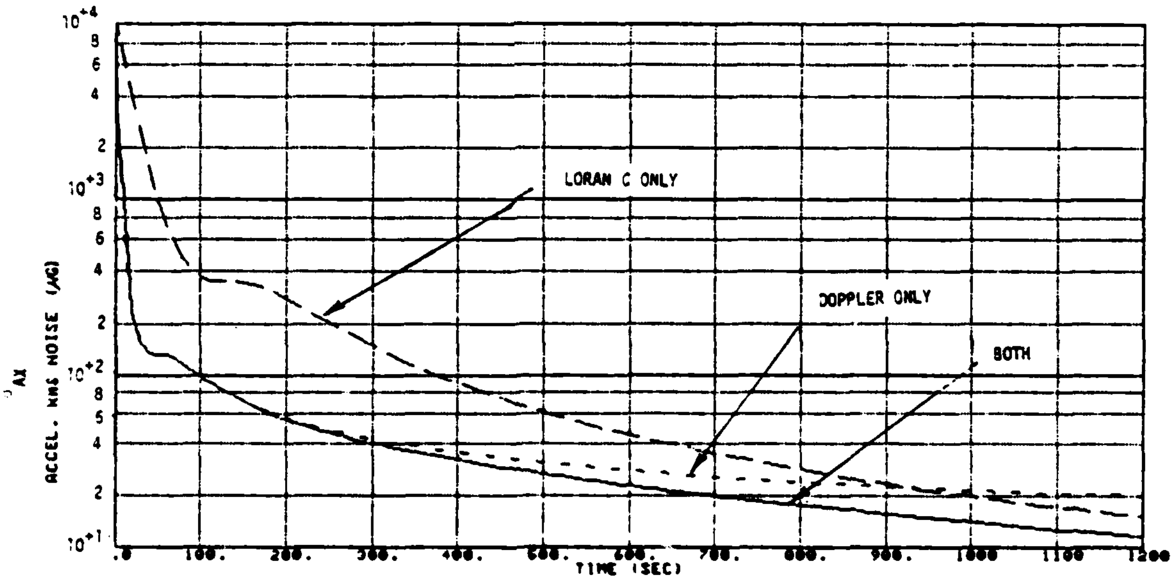

Figure 4.4b Accelerometer Accuracy σ_{AX}
(Nominal Noise Levels of Sensors for Alignment Data)

Table 4.3

Nominal Sensor Error Levels for Inertial Measurement Unit Alignment Analysis and Coefficient Estimation Analysis

QUANTITY	SENSOR	1 SIGMA RANDOM ERROR	BIAS DRIFT RATE
Position	LORAN-C	20 ft	0.03 ft/sec
	Radio Range Transponder	3 ft	--
Velocity with respect to water	Doppler Sonar	0.1 Kt	10^{-4} ft/sec^2 caused by current shear
Yaw Rate	Autopilot Grade Angular Rate Gyroscope	5 °/hr	--
Yaw Rate	Navigation Grade Angular Rate Gyroscope	0.0002°/hr	small
Translational Acceleration	Translational Accelerometer (Navigation Grade)	600 μg	--

Table 4.4

Sensitivity of Alignment to Changes in Noise Levels
(Standard Errors After 15 Minutes of Calibration)

NOMINAL NOISE LEVELS		
ALIGNMENT DATA FROM:	σ_{GYRO} (DEG/HR)	σ_{AX} (μG)
LORAN-C	.0106	23.4
DOPPLER	.0124	22.7
LORAN + DOPPLER	.00717	15.7

DRIFT CURRENT = 5* NOMINAL		
ALIGNMENT DATA FROM:	σ_{GYRO} (DEG/HR)	σ_{AX} (μG)
LORAN	.0106	23.4
DOPPLER	.0478	109
LORAN + DOPPLER	.0102	22.6

LORAN BIAS DRIFT = 10* NOMINAL		
LORAN-C	.0742	186.
DOPPLER	.0124	22.7
LORAN + DOPPLER	.00797	22.4

DOPPLER NOISE (σ_v)=1/2 NOMINAL		
LORAN-C	.0106	23.4
DOPPLER	.0122	22.1
LORAN + DOPPLER	.00706	15.4

LORAN NOISE (σ_x)=10* NOMINAL		
LORAN-C	.0272	62.6
DOPPLER	.0124	22.7
LORAN + DOPPLER	.00869	20.5

GYRO PICK UP (σ_q)= 500* NOMINAL		
LORAN-C	1.001	65.9
DOPPLER	1.001	45.9
LORAN + DOPPLER	1.001	44.7

errors are nearly proportional to the Loran-C bias drift. The hydrodynamic coefficient estimation errors shown in Figure 4.5 for System 6 (aligned inertial unit aided by radio position fix) are nearly proportional to the alignment errors. For example, the estimation accuracy of Y_v would be degraded from about 2% to 20% (water current present) by a factor of 10 increase in Loran-C bias drift.

(2) If only Doppler sonar is used as an independent measurement, then both rate gyro and accelerometer alignment errors are nearly proportional to the drift current (water current gradient) magnitude. The hydrodynamic coefficient estimation errors shown in Figure 4.5 for System 5 (aligned inertial unit aided by Doppler sonar) are nearly proportional to the alignment errors. For exmple, the estimation accuracy of Y_v would be degraded from about 2% to 20% (water current present) by a factor of 10 increase in water current gradient.

(3) If both Loran-C and Doppler measurements are available, then alignment accuracies degrade only slightly when either Loran-C noise or water current variations increase.

4.3 EVALUATION OF CANDIDATE SYSTEMS FOR HYDRODYNAMIC COEFFICIENT ESTIMATION

This section presents the hydrodynamic coefficient estimation accuracies which are attainable using several candidate sensor systems. Table 4.5 lists the sensors employed by the seven systems. The aligned inertial measurement unit employs three orthogonal axis accelerometers and three orthogonal axis angular rate gyroscopes. It is assumed that the IMU (System 7) has been aligned to the accuracy level in Table 4.4 for "Nominal Noise Levels" with Loran-C available. (The alignment of the inertial system is feasible using either Loran-C or Doppler sensors, or both. The use of Loran-C only is the simplest to implement in the field due to the difficulty of Doppler sonar installation.)

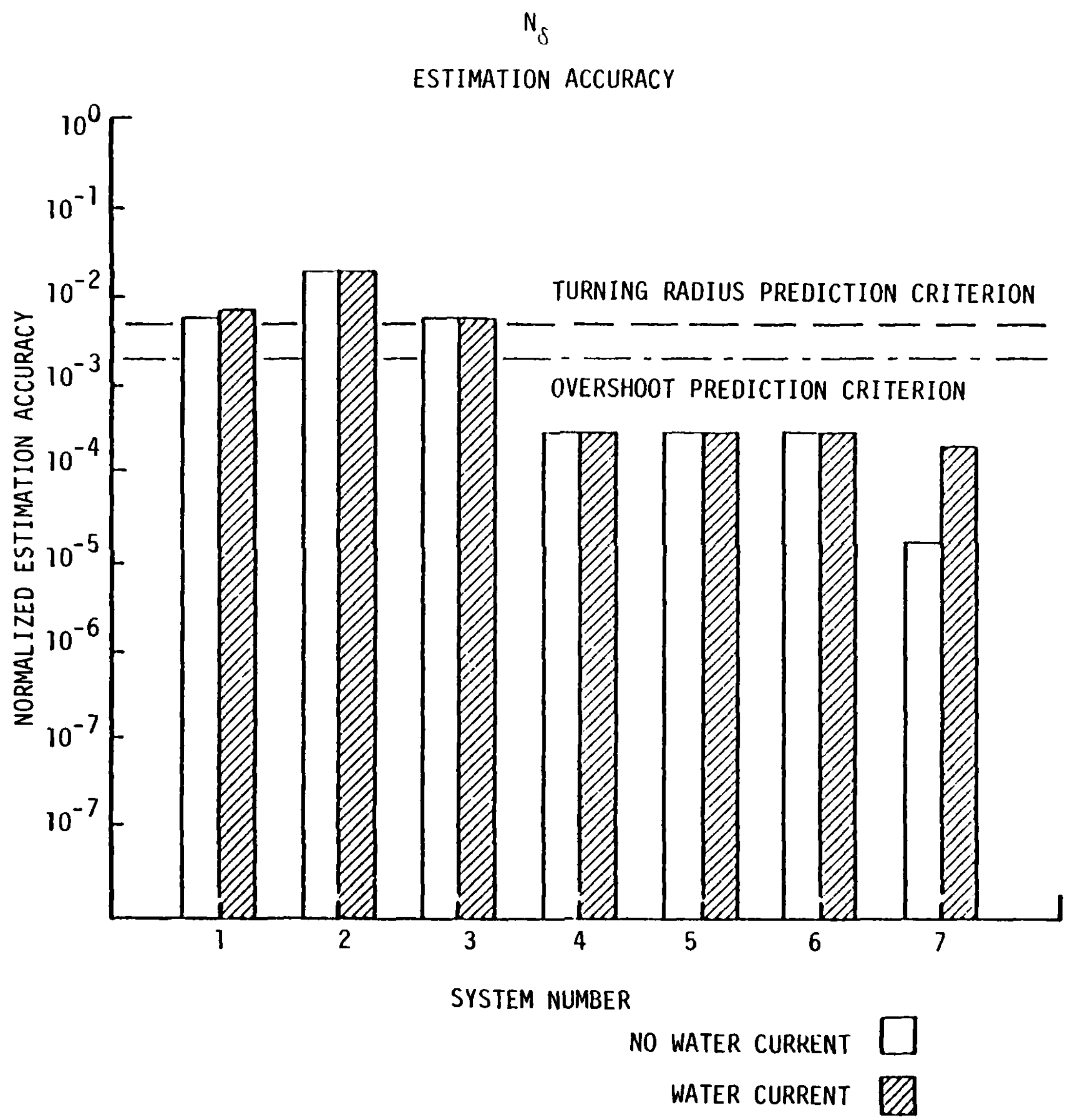

Figure 4.5 Coefficient Accuracy

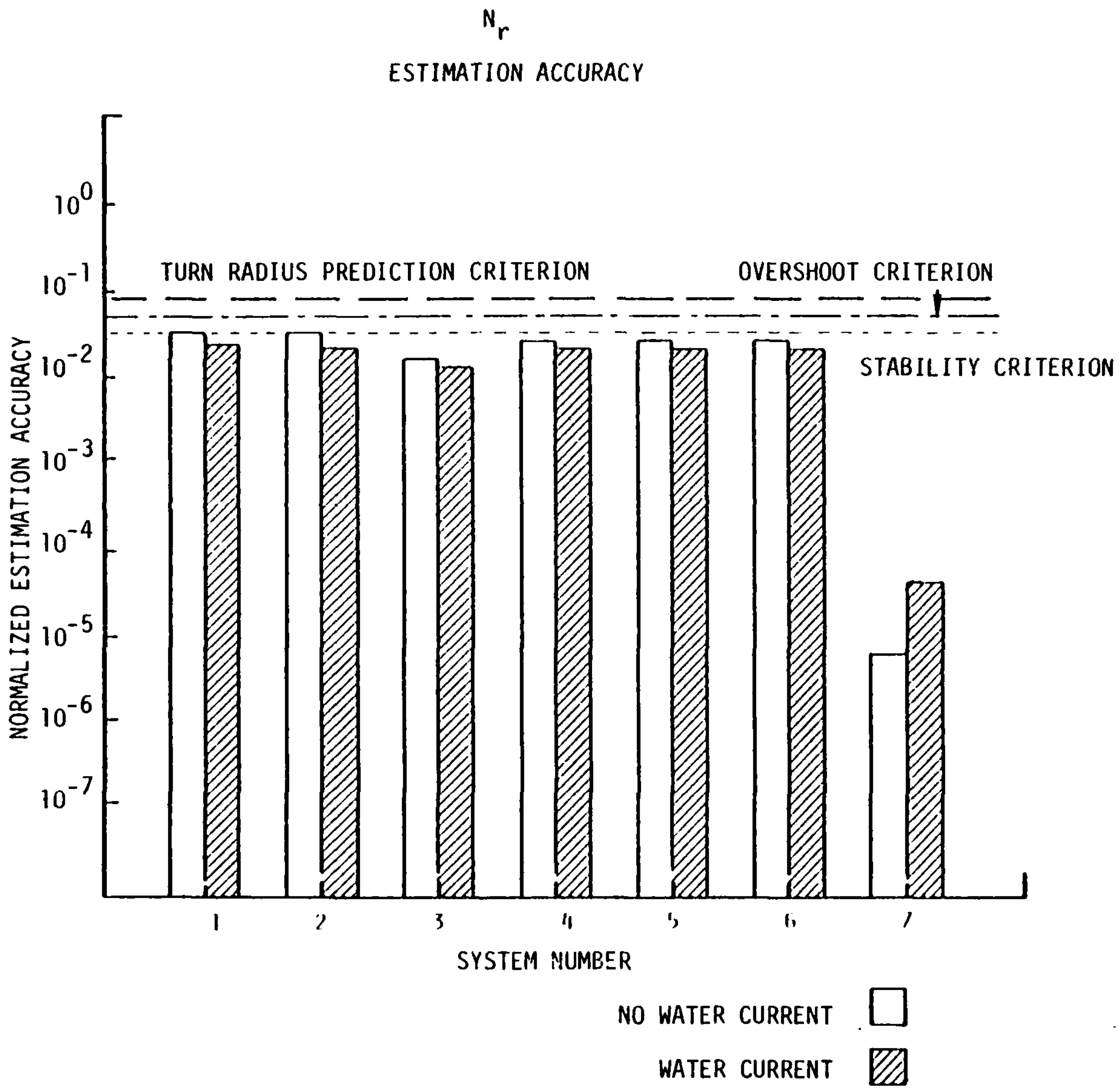

Figure 4.5 (Continued)

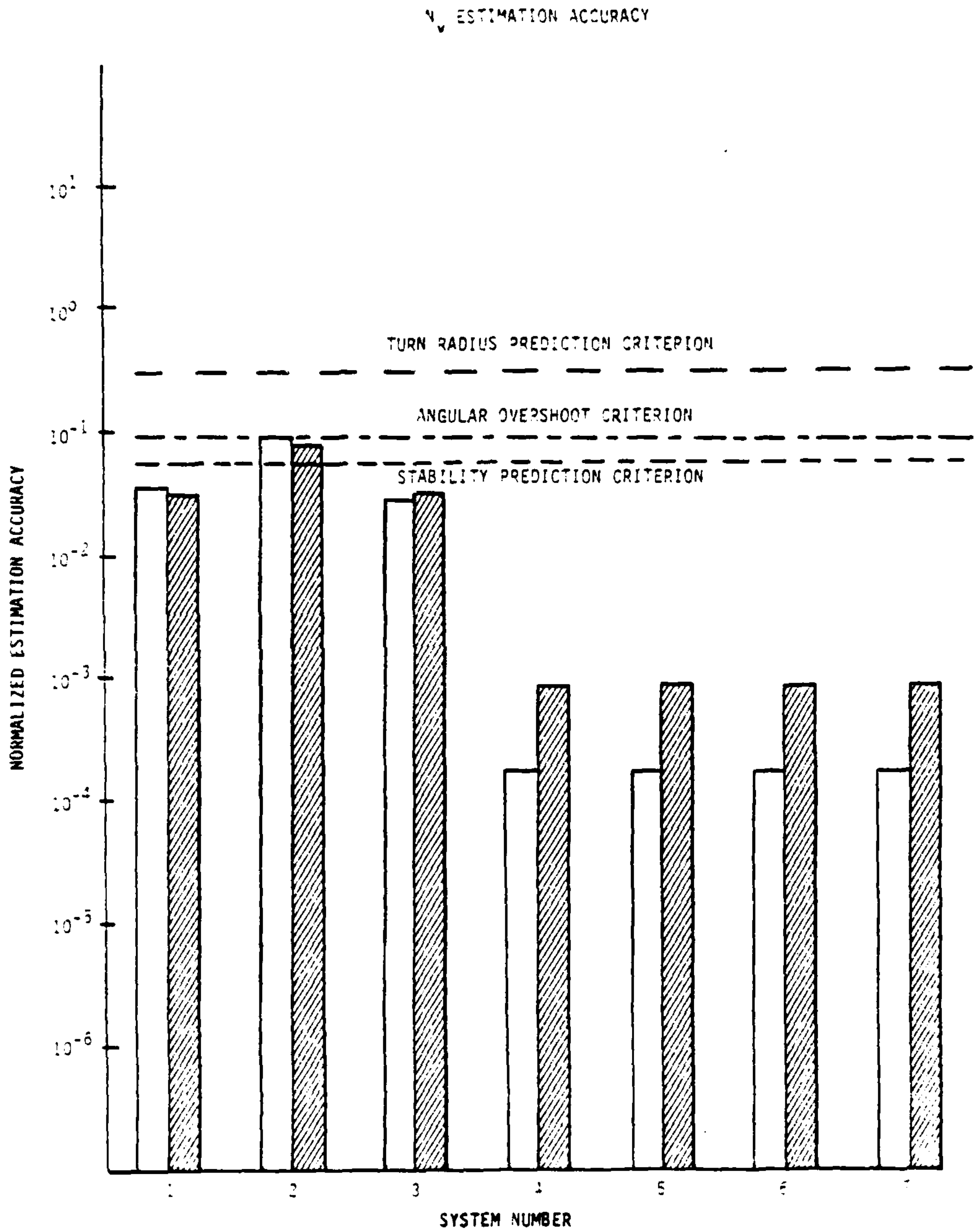

Figure 4.5 (Continued)

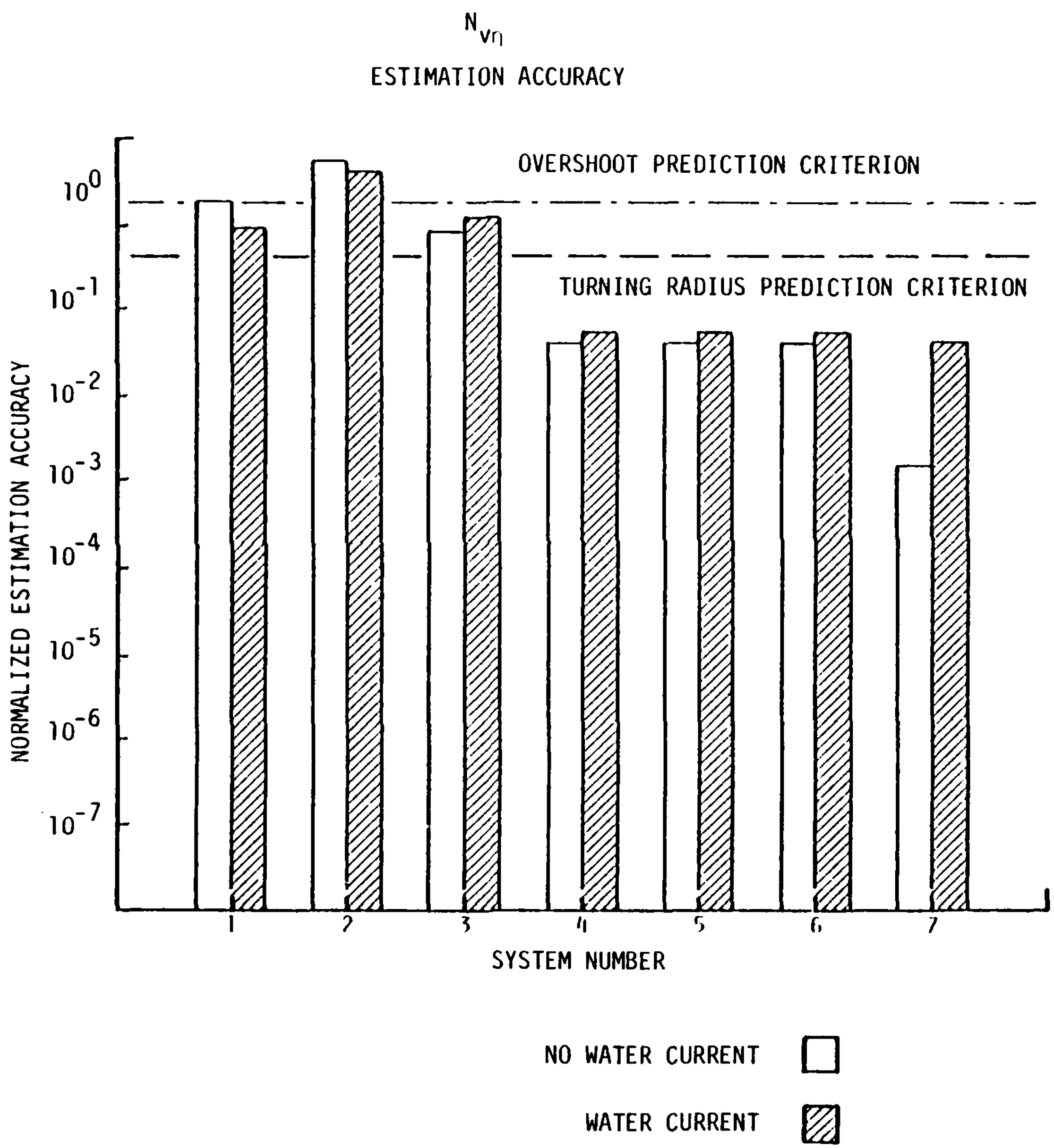

Figure 4.5 (Continued)

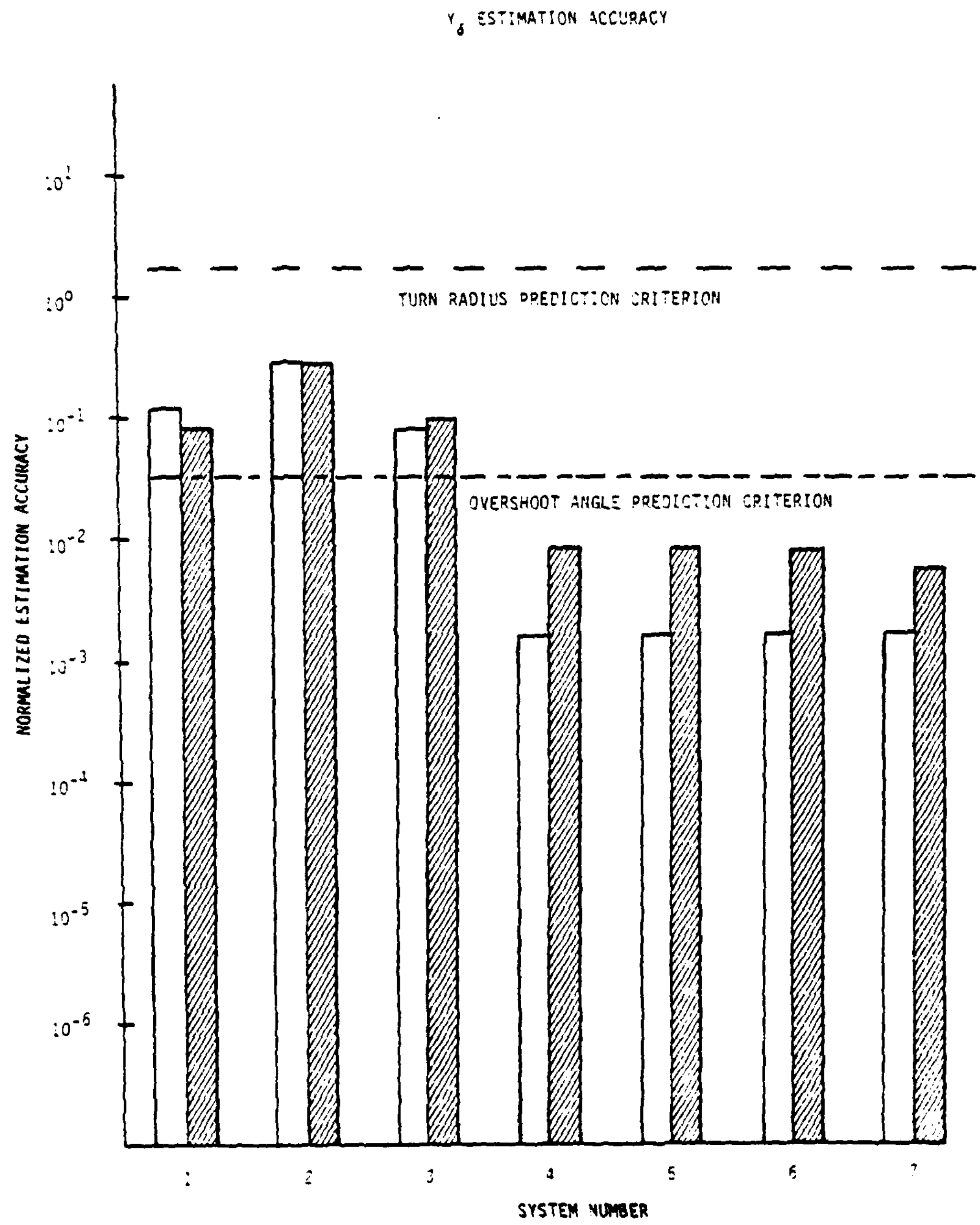

Figure 4.5 (Continued)

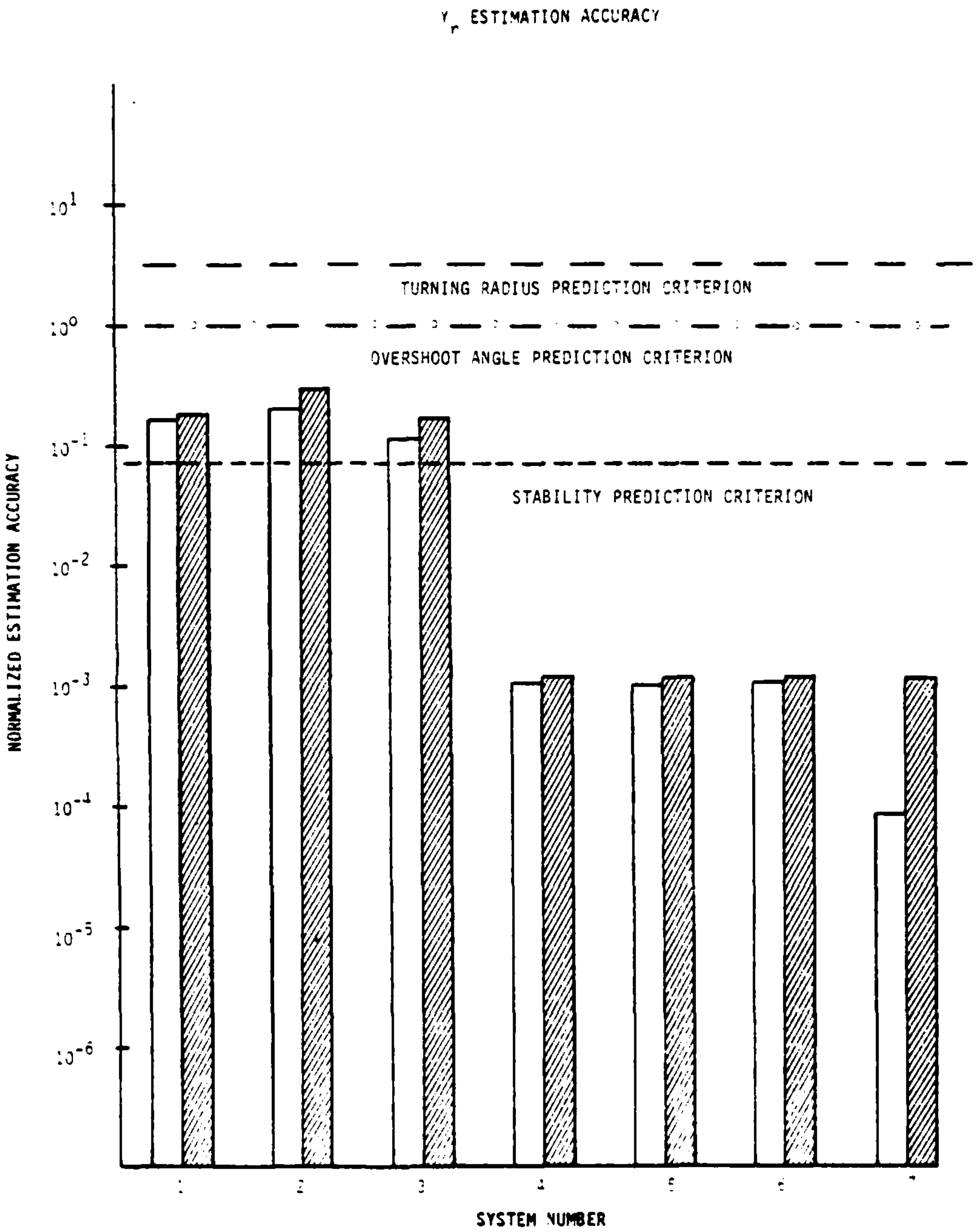

Figure 4.5 (Continued)

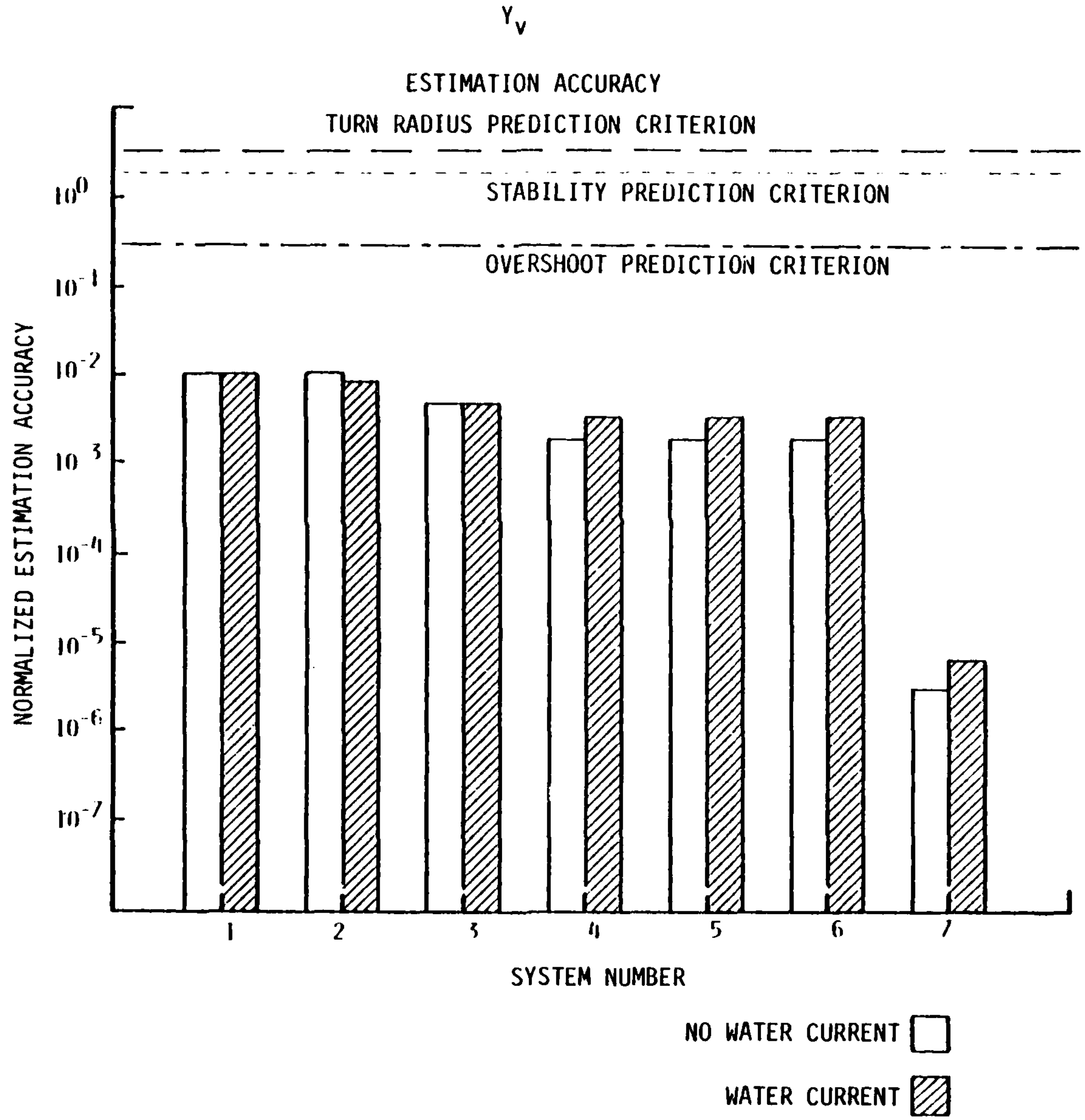

Figure 4.5 (Continued)

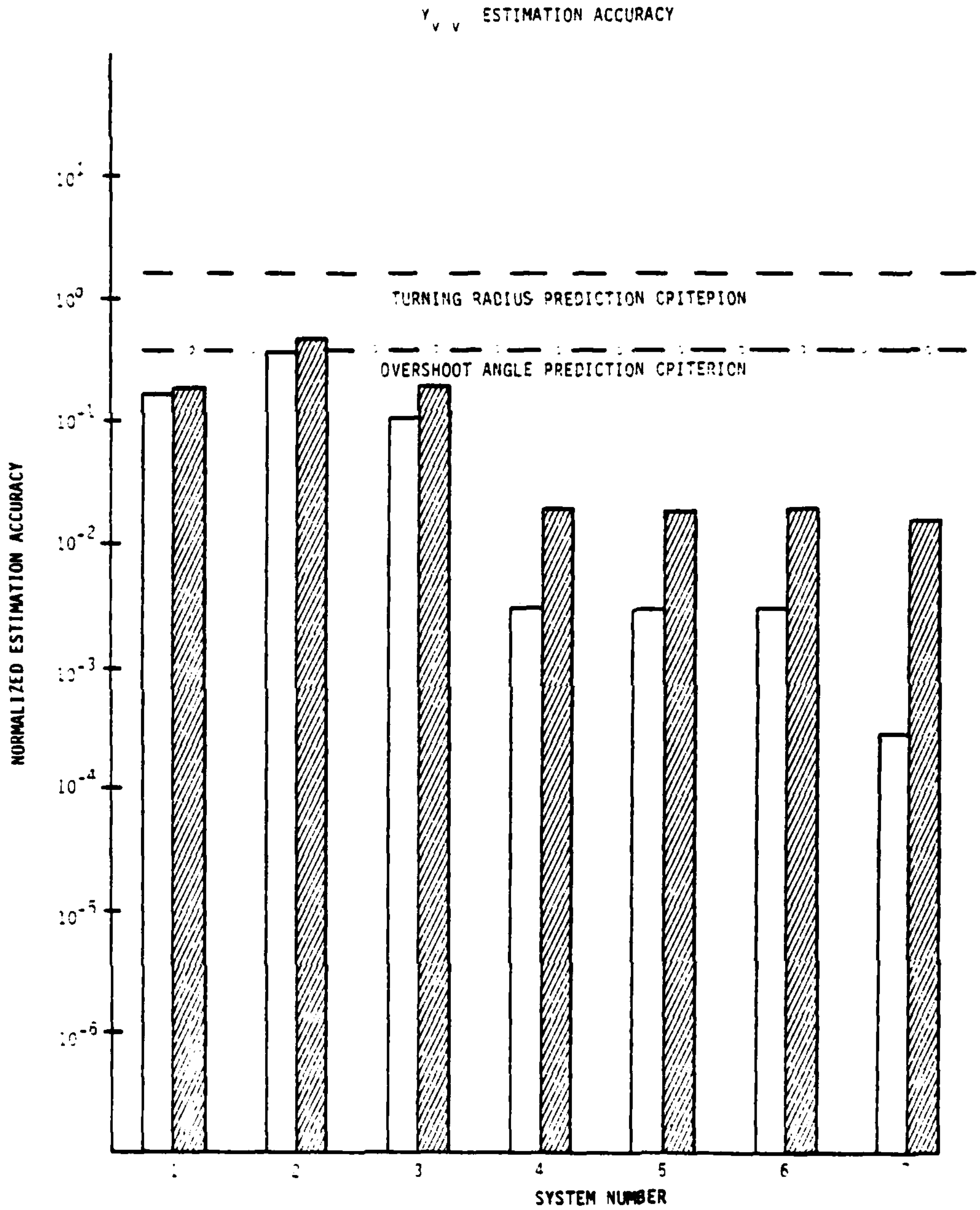

Figure 4.5 (Continued)

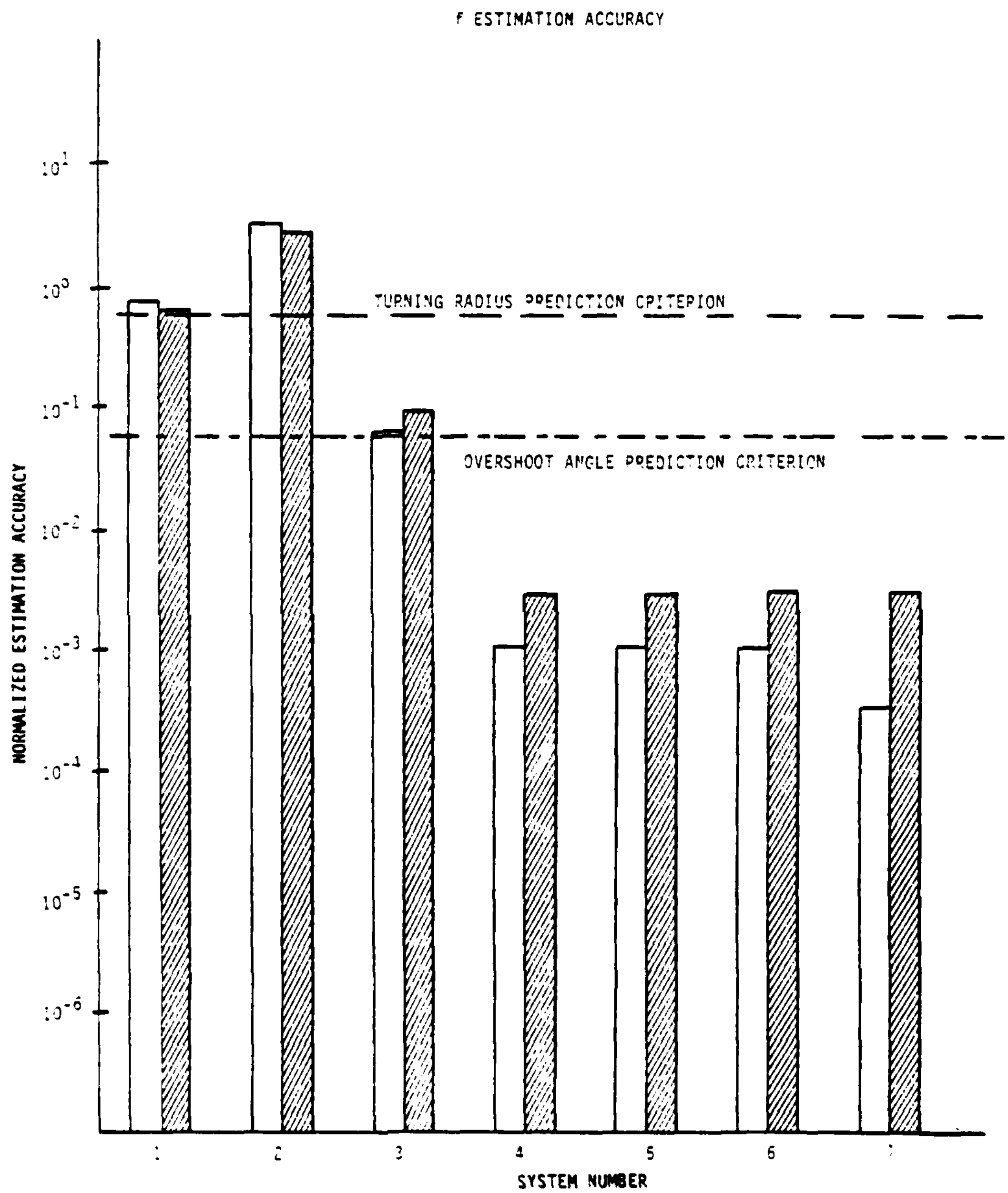

Figure 4.5 (Continued)

Table 4.5
Instrument System Components

SYSTEM NUMBER	SHIPS GYROCOMPASS	YAW RATE GYRO	DUAL AXIS DOPPLER SONAR	DUAL AXIS ACCELEROMETERS	ALIGNED INERTIAL MEASUREMENT	RADIO POSITION FIX
1						■
2			■			
3			■			■
4		■		■		
5		■	■			
6		■	■	■		
7			■		■	■

The coefficient accuracy analysis assumes that all sensor measurements are corrupted by random errors at the level defined in Table 4.3. It also assumes the presence of the systematic errors listed in Table 4.6. These systematic errors reflect residual sensor calibration uncertainty as well as uncertainty in knowledge of the characteristics of the vessel/waterway system. This second category includes water current shears and uncertainty in the exact vessel mass center location.

Reference 20 covers analytic methods for the determination of the accuracy of system identification results given sensor noise levels and systematic error levels.

Figure 4.5 presents bar-graph charts of nine hydrodynamic coefficient estimation uncertainty levels using each of the seven candidates. Two coefficient uncertainty levels are presented for each system. The calculation of the first accuracy level assumes that the random noises defined in Table 4.3 and the systematic errors of Table 4.5 (except for water current) are present. The second accuracy level assumes that a water current gradient provides an additional source of error. The magnitude of the gradient is 0.6 knots of current/15 nmi of ship motion.

The dashed horizontal line in each graph indicates the coefficient accuracy level required to predict ship's turning radius to within $\pm 3\%$. The dotted horizontal line in the graphs for each of the four linear hydrodynamic coefficients (Y_v, Y_r, N_v, N_r) indicates the coefficient accuracy level required to predict the σ_1 stability index to within $\pm 3\%$. The normalized sensitivities of definitive maneuvering characteristics presented in Section 4.2.2 determine these required accuracy levels. The required accuracy of estimation of a typical hydrodynamic coefficient θ for predicting a given definitive maneuvering characteristic $\overline{\Phi}$ is defined here as

$$\Delta\theta/\theta = 0.03/\overline{\Phi}_\theta$$

This definition evolves from the definition of normalized sensitivity of Section 3.2.2.

Table 4.6

Systematic Error Sources

SYMBOL	DEFINITION	MAGNITUDE
ΔX_{cg}	ERRORS IN KNOWLEDGE OF LOCATION OF SHIP MASS CENTER WITH RESPECT TO PACKAGE LOCATION	1 FT
ΔY_{cg}		0.3 FT
$\Delta\psi$	ERROR IN PACKAGE YAW ATTITUDE WITH RESPECT TO SHIP LONG AXIS	0.01 RADIAN
K_{AX}	ACCELEROMETER SCALE FACTOR ERROR	50 PARTS/ MILLION (ppm)
K_{AY}		
B_{AX}	ACCELEROMETER BIAS (BEFORE ALIGNMENT)	60 μ GRAVITY
B_{AY}		
K_R	YAW RATE GYRO SCALE FACTOR ERROR	50 ppm
B_R	YAW RATE GYRO BIAS (BEFORE ALIGNMENT)	0.02 /HR
ΔX_D	ERROR IN KNOWLEDGE OF DOPPLER SENSOR LOCATION	1 FT
ΔY_D		0.3 FT
K_u	DOPPLER SCALE FACTOR	10 ppm
K_v		
b_u	DOPPLER BIAS	0.05 FT/SEC
b_v		
K_{XB}	RADIO POSITION FIXING SCALE FACTOR	20 ppm
K_{YB}		
b_{XB}	RADIO POSITION FIXING BIAS	2 FT
b_{YB}		

Two caveats are necessary in deriving insight from the levels of required accuracy for hydrodynamic coefficients.

(1) The 3% level is somewhat arbitrary. One cannot say, for example, that a vessel maneuvering simulation is completely inadequate because it predicts turning radius with 4% error. The converse is also true. Coefficient estimation accuracy requirements are, however, approximately linear with respect to the percentage error in prediction of maneuvering characteristics. If the allowable percentage error is 6% instead of 3%, then all of the dashed lines of Figure 4.5 are twice as high as presently indicated.

(2) Each of the bar graphs of Figure 4.5 indicates the estimation accuracy of a single hydrodynamic coefficient. Placing bounds, represented by the dashed lines, on any one of these graphs implicitly assumes that errors in prediction of a maneuvering characteristic are due only to that single coefficient. The total uncertainty in a normalized maneuvering characteristic $\bar{\Phi}$, such as turning radius, is given by

$$\Delta\phi = \{\sum_i [(\bar{\Phi}_\theta) \cdot (\Delta\theta_i/\theta_i)]^2\}^{1/2} .$$

In other words, the total uncertainty is the root sum square of the contributions in uncertainty due to normalized error in knowledge of each of the hydrodynamic coefficients $(\Delta\bar{\theta}_i/\theta_i)$.

4.4 CONCLUSIONS OF SENSOR REQUIREMENTS STUDY

The following conclusions are based on Figure 4.5 and Table 4.5.

(1) The aligned inertial measurement system (alignment aided by radio position fix and Doppler sonar), system 7, provides some coefficient estimation accuracies which are significantly better than those obtained with any other system.

(2) Systems 4 through 6 (yaw rate gyro with sonar and/or accelerometers) meet or exceed all estimation accuracy criteria on turn radius, stability, and overshoot prediction.

(3) System 1 using radio position fix only, can meet some, but not all, estimation criteria. It is doubtful that a complete, acceptable CAORF type of model could be determined using position-fix data only. The estimation of a model with fewer parameters might be feasible, however. Such a model might be one involving only linear hydrodynamic coefficients (Y_v, Y_r, Y_δ, N_v, N_r, N_δ).

(4) Water currents significantly degrade lateral force coefficient (Y_δ, Y_r, Y_v, $Y_{v|v|}$) when the more accurate systems are used. Currents apparently do not significantly degrade yaw moment coefficients (N_δ, N_r, N_v, $N_{v\eta}$).

(5) Those coefficients which most critically affect prediction of maneuvering characteristics tend to be most easily estimated by the system identification process.

V. MANEUVER TEST PLAN

This section presents a complete plan for conducting maneuvers to gather data for system identification of the river tow hydrodynamic model. The elements of the complete plan are

- a maneuver menu;
- a maneuver sequence; and
- a recommended test site.

A complete sequence of maneuvers can be completed in approximately nine days of testing at 10 hours of operation per day. An abbreviated, but adequate, sequence can be completed in three days. Two potential test sites are Lake Pontchartrain and the Barkley Dam pool.

5.1 MANEUVER MENU

The maneuver menu is a list of 20 basic maneuver types to be executed during the maneuver testing of the river tow. Each maneuver isolates a subset of hydrodynamic phenomena (i.e. coefficients). The behavior of the tow during any one maneuver ideally should depend strongly only on a small subset of the total set of hydrodynamic coefficients. The effects of uncertainties in other coefficients on that particular maneuver are then minimized. The complete maneuver menu should cover all subsets of coefficients. The system identification data processing will build up a complete hydrodynamic model by processing data from individual maneuvers sequentially.

The use of various maneuvers to isolate the effects of various elements of the hydrodynamic model is analogous to the use of oblique towing and of a planar motion mechanism (PMM) in tow tank testing [21]. Oblique towing isolates the static effects: those due to sideslip and combined rudder-sideslip. The PMM can isolate the effects of yawing motion from the above

effects. Small amplitude motions isolate the effects of the first-order coefficients (e.g. Y_v, N_δ), while larger amplitude maneuvers depend both on first-order coefficients and on higher order coefficients.

5.1.1 Requirements

The following are the criteria for selection of maneuvers to be included in the maneuver menu.

(1) Each hydrodynamic coefficient (i.e. each type of hydrodynamic phenomena) must affect the behavior of the tow in at least one maneuver.

(2) Each maneuver should isolate the effects of a small set of coefficients. In other words, the behavior of the tow during a given maneuver should depend strongly on a small subset, say five or six, of the total number of coefficients. It should be relatively independent of all other coefficients. Table 5.1 lists coefficient subsets which will be isolated by test maneuvers.

(3) The rudder and propulsion commands must be simple enough so that they can be implemented by a helmsman. This is an important consideration in testing any vehicle which does not have a programmable autopilot. The use of such an autopilot would allow the execution of very complex input commands.

(4) No maneuver should endanger the river tow.

5.1.2 Maneuver Types in the Menu

Table 5.2 lists 20 maneuver types to be executed by the river tow during the maneuvering trials. Most of the maneuvers are of the Kempf overshoot (or zig-zag) maneuver class [11]. The typical procedure for conducting an overshoot test is as follows:

Table 5.1
Hydrodynamic Coefficient Subsets

SUBSET #1	TITLE	COEFFICIENTS
1	Linear Hull, Rudder Coefficients	Y_* Y_v Y_r $Y_{\delta s}$ $Y_{\delta f}$
2	Nonlinear Hull Coefficients	$Y_{v\|v\|}$ $Y_{r\|r\|}$ $Y_{r\|v\|}$ $Y_{v\|r\|}$ $N_{v\|v\|}$ $N_{r\|r\|}$ $N_{r\|v\|}$ $N_{v\|r\|}$ X_{vr} X_{vv} X_{rr}
3	Nonlinear Rudder Coefficients	$Y_{\delta s\|\delta s\|}$ $Y_{\delta f\|\delta f\|}$ $N_{\delta s\|\delta s\|}$ $N_{\delta f\|\delta f\|}$ $X_{\delta s\delta s}$ $X_{\delta f\delta f}$
4	Propulsion Coefficients	X_*, X_n, X_{nn}
5	Rudder, Propulsion Interaction Function	$u_p(n)$ model structure unknown
6	Hull, Propulsion Interaction Coefficients	Y_{vn} $Y_{v\|v\|n}$ Y_{rn} N_{vn} $N_{v\|v\|n}$ N_{rn} X_{vvn}
7	Hull Force, Moment Functions for Large Sideslip Angle $\|\sin\beta\| > 0.3$	$Y(v)$ $N(v)$ model structure unknown
8	Hull Force, Moment Functions for Large Dimensionless Yaw Rates $\|r'\| = \|r\ell/u\| > 1.0$	$Y(r')$ $N(r')$ model structure unknown
9	Added mass	$Y_{\dot v}$ $Y_{\dot r}$ $N_{\dot v}$ $N_{\dot r}$ $X_{\dot u}$

(1) Steady ship at constant course and speed.

(2) Deflect the rudder at maximum rate to a preselected angle, say 20 degrees, and hold until a preselected change of heading angle, say 10 degrees, is reached.

(3) At this point, deflect the rudder at maximum rate to an opposite (checking) angle of 20 degrees and hold until the execute change of heading angle on the opposite side is reached. This completes the overshoot test.

(4) If a zig-zag test is to be completed, again deflect the rudder at maximum rate to an angle of 20 degrees in the first direction. This cycle can be repeated through the third, fourth, or more executes.

The test described above would be called a 20°/10° zig-zag maneuver.

The advantages of the zig-zag maneuver with regard to the criteria of Section 5.1.1 are as follows.

(1) The effects due to first degree coefficients can be isolated by choosing small amplitude heading change limits and rudder deflection amplitudes.

(2) Maneuvers using higher amplitude rudder deflections and heading change limits will additionally depend on higher degree coefficients.

(3) Accelerating or decelerating zig-zag maneuver additionally depend on the rudder force multiplication factor due to increased or decreased blowing of the propeller wake over the rudder.

(4) The rudder history during a zig-zag maneuver has the pattern of a square wave. Such a test input signal is widely used in the testing of many types of dynamic systems (e.g. aircraft handling-qualities testing, electronic circuit response). The periodic square wave contains an infinitely wide band of frequencies and will excite nearly all modes of motion of the system.

(5) The rudder commands which must be executed by the helmsman are quite simple and can be implemented easily.

(6) The execution of the zig-zag maneuver inherently controls heading. The heading of the river tow will not wander indefinitely from its starting value during the maneuver. This is particularly important if the test is to be executed in a somewhat restricted inland waterway.

(7) Zig-zag maneuvering trials have already been executed using a river tow [21,22].

The maneuvering menu includes accelerated, decelerated, and coasting zig-zag maneuvers. These maneuvers give information on propeller/rudder interaction for values of η (propulsion coefficient) not close to 1.0. The maneuvers are performed by changing the propeller rotation rate to a new value as the zig-zag maneuver begins. For example, suppose that a propeller rate of 80 rpm will propel the vessel at 4 knots. Increasing the rate to 160 rpm as a 20°/25° zig-zag maneuver begins will very rapidly yield a propulsion coefficient of nearly 2.0. The propulsion coefficient will relax toward 1.0 as the tow accelerates. The tow will not return to a propulsion coefficient of exactly 1.0 during the zig-zag maneuver because of the added resistance due to the lateral motion.

The maneuver above can be parameterized as 20°/25°/2 (20° of rudder, 25° of heading change, and $\eta = 2$). If the maneuver had been a coasting zig-zag maneuver, it would have been described as a 20°/25°/0 zig-zag maneuver. Decelerating zig-zag maneuvers would have $\eta < 0$.

A second maneuver class is the rudder kick turn, or the accelerating turn. This maneuver begins with the river tow moving forward slowly, nominally at a speed less than 4 knots. The maneuver is executed by simultaneously deflecting the steering rudder and increasing the propeller turns. The interaction of the rudder with the propeller race causes a strong lateral force at the stern. This lateral force is the "rudder kick."

The accelerating turn maneuver gives information on the rudder/propeller race interaction. This interaction is a primary mechanism for maneuvering at slow speeds by vessels which lack steerable propulsors. (It is absolutely vital to most large ocean-going merchant ships, which are of single-screw design.) Like the zig-zag maneuver, two parameters define the accelerating turn's characteristics. The two parameters are rudder deflection, δ, and propulsion ratio change, η. The typical procedure for conducting an accelerating turn test is as follows.

(1) Initially, the vessel is propelled forward at a relatively slow rate, say 4 knots, with screws turning to maintain that speed ($\eta = 1$).

(2) Deflect the rudder at maximum rate to a preselected angle, δ, say $\delta = 25°$.

(3) Simultaneously increase propeller rate of turns initially to give a preselected propulsion ratio η, say $\eta = 2$. For an initial speed of 4 knots, this will require making turns for 8 knots.

(4) Maintain the δ of (2) and the propeller rate of (3) for approximately a 360° heading change. (Maintaining a constant propeller rotation rate gives a variable propulsion ratio during the maneuver. η will increase further from 2 if the vessel slows during the turn.)

The test described above would be called a 25°/2 accelerating turn maneuver having an initial speed of 4 knots.

The rudder kick turn can also be conducted on many river tows while decelerating. This requires the use of the flanking rudders. Since these rudders are located ahead of the propellers, their effectiveness is enhanced when the propellers are thrusting backward.

A third maneuver class is the coasting or decelerating turn. This maneuver begins with the river tow moving forward at a nominal speed between 4 and 12 knots. The maneuver is executed by simultaneously deflecting the steering rudder and decreasing

the propeller turns. This maneuver gathers information on coefficients which model the rudder effectiveness for $\eta < 1$ (coasting turn) or $\eta < 0$ (decelerating turn). Experiments conducted with $\eta \cong 0$ give information on parameters which could model the maneuvering characteristics of the vessel following a propulsion casualty. Coasting turns can be parameterized using the same conventions as those used to define the accelerating turn. Now, however, the second parameter will be less than one or may possibly be zero. A coasting turn using 25° of rudder deflection and zero propeller rate would be called a 25°/0 coasting turn.

Two maneuvers which are commonly performed during maneuvering trials turn out to be relatively inefficient for the collection of data for the purpose of system identification. These two maneuvers are the turning circle and the Dieudonne spiral [11]. They are primarily steady-state maneuvers. Execution of the turning circle may require nearly a half hour, but only yields limited information on ship hydrodynamic coefficients. This is because once the ship enters the steady-state portion of the turn, no new information is acquired by the continuously recording instrument system. The same problem exists to a somewhat lesser degree with the use of the Dieudonne spiral. The vessel will be nearly in steady state during the execution of most of this maneuver.

Data from primarily steady-state maneuvers can be used for the identification of hydrodynamic coefficients [23]. However, the amount of information collected per unit time is much lower than that collected during the zig-zag and accelerating/ decelerating turns. The execution of a spiral maneuver by a test vessel would be useful primarily in that its raw results (turning rate as a function of rudder angle as opposed to identified coefficient values) could be compared directly to similar results available for numerous other vessels.

The execution of a turning circle does provide information about the magnitude and direction of water currents in the test area. For this reason, the schedule of test maneuvers includes a turning circle executed at the beginning and at the end of each day of testing. (The execution of a complete turning circle may not be possible on a restricted inland waterway.)

Table 5.2 is the menu of maneuvers to be executed during the test plan. Section 5.2 will cover the sequence for the execution of these maneuvers. Most of the maneuvers in Table 5.2 will be executed at least twice in the complete maneuver sequence. This is to allow collection of data for model validation. (Validation is accomplished by predicting the vessel behavior during maneuvers not used to identify coefficients [6].)

Figure 5.1 illustrates the four maneuver areas required to execute the test maneuvers. The four areas are designated A, B, C, or D in Table 5.2.

5.2 MANEUVER SEQUENCE

The order of execution of the maneuvers defined in Section 5.1 is largely arbitrary. The only consideration in choosing an order of execution is the minimization of total test time. An effective strategy for minimizing test time is the following:

- Execute all zig-zag maneuvers in ahead motion using maneuver geometry A. Alternate between test maneuver box 1 and test maneuver box 2. This will require the execution of a 180° turn at the end of each zig zag. Attaining exact speed and heading conditions at the beginning of each is not critical.
- Similarly execute all zig-zag maneuvers in astern motion.
- Execute acceleration ahead in area A.
- Execute wide (rudder = 10°, 20°) accelerating turns in maneuver area D.

Table 5.2 Maneuver Menu

CATEGORY	MANEUVER TYPE NUMBER	PARAMETERS	INPUT	COEFFICIENT SUBSETS		DIRECTION OF TRAVEL	MANEUVER GEOMETRY AREA	TIME REQUIRED FOR EXECUTION	PRIORITY
				PRIMARY	SECONDARY				
Zig-Zag	1	5°/5°/1	Steering Rudder	1	-	Ahead	A	10 min.	2
	2	10°/10°/1		1	-			10	1
	3	20°/20°/1		1	2			10	1
	4	20°/40°/1		2	1			20	3
	5	40°/40°/1		3	2			20	2
	6	5°/5°/1	Flanking Rudder	1	-	Astern		10	1
	7	10°/10°/1		1	-			10	1
	8	10°/20°/1		1	2			10	1
	9	20°/40°/1		2	1			20	3
	10	40°/40°/1		3	2			20	2
	11	5°/5°/3	Steering Rudder, RPM	5	1	Ahead		10	2
	12	10°/10°/3		5	1			10	1
	13	20°/20°/3		5	1			10	1
	14	20°/40°/3		5	6			20	3
	15	40°/40°/3		5	6			20	2
	16	5°/5°/-1	Flanking Rudder, RPM	5	1	Astern		10	2
	17	10°/10°/-1		5	1			10	1
	18	20°/20°/-1		5	1			10	1
	19	20°/40°/-1		5	6			20	3
	20	40°/40°/-1		5	6			20	2
	21	5°/5°/3		5	1			10	2
	22	10°/10°/3		5	1			10	1
	23	20°/20°/3		5	1			10	1

Table 5.2 (Continued)

CATEGORY	MANEUVER TYPE NUMBER	PARAMETERS	INPUT	COEFFICIENT SUBSETS		DIRECTION OF TRAVEL	MANEUVER GEOMETRY AREA	TIME REQUIRED FOR EXECUTION	PRIORITY
				PRIMARY	SECONDARY				
Zig-Zag (Cont.)	24	20°/40°/3		5	6	Astern	A	20	3
	25	40°/40°/3		5	6			20	2
	26	5°/5°/-1		5	1			10	2
	27	10°/10°/-1	Steering Rudder, RPM	5	1	Ahead		10	1
	28	20°/20°/-1		5	1			10	1
	29	20°/40°/-1		5	6			20	3
	30	40°/40°/-1		5	6			20	2
	31	5°/5°/0		5	1			10	2
	32	10°/10°/0		5	1			10	1
	33	20°/20°/0		5	1			10	1
	34	20°/40°/0		5	1			20	3
	35	40°/40°/0		5	1			20	2
	36	5°/5°/0		5	1			10	2
Acceler-ating Turn	37	10°/10°/0	Flanking Rudder, RPM	5	1	Astern		10	1
	38	20°/20°/0		5	1			10	1
	39	20°/40°/0		5	1			20	3
	40	40°/40°/0		5	1			20	2
	41	10°/2	Steering Rudder, RPM	5	2	Ahead	D	20	3
	42	20°/2		5	2			20	2
	43	40°/2		5	2		C	20	1
	44	10°/0		5	2		D	20	3
	45	20°/0		5	2			20	2
	46	40°/0		5	2		C	20	1

Table 5.2 (Concluded)

CATEGORY	MANEUVER TYPE NUMBER	PARAMETERS	INPUT	COEFFICIENT SUBSETS		DIRECTION OF TRAVEL	MANEUVER GEOMETRY AREA	TIME REQUIRED FOR EXECUTION	PRIORITY
				PRIMARY	SECONDARY				
Accelerating Turn (Cont.)	47	10 /-1	Flanking Rudder, RPM	5	2	Astern	D	20	3
	48	20 /-1		5	2			20	2
	49	40 /-1		5	2		C	20	1
	50	10 /2		5	2		D	20	3
	51	20 /2		5	2			20	2
	52	40 /2		5	2		C	20	1
	53	10 /0		5	2		D	20	3
	54	20 /0		5	2			20	2
	55	40 /0		5	2		C	20	1
	56	10 /-1	Steering Rudder, RPM	5	2	Ahead	D	20	3
	57	20 /-1		5	2			20	2
	58	40 /-1		5	2		C	20	1
Lateral Transfer	59	-	Bow Thruster, Steering Rudder, RPM	7	2		B	20	2
Pure Rotation	60	-		7	2			20	2
Acceleration	61	-	RPM	4	-	Astern	A	20	2
	62	-		4	-	Ahead		20	1
Crash Stop	63	-		4	-			20	1

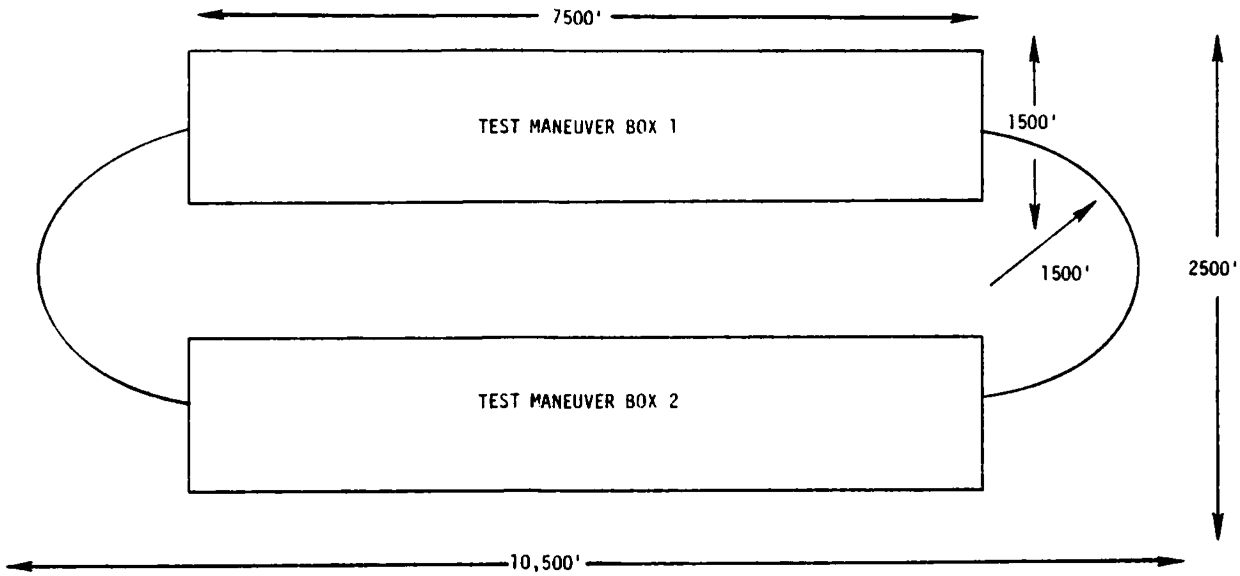

Figure 5.1(a) Maneuver Area A

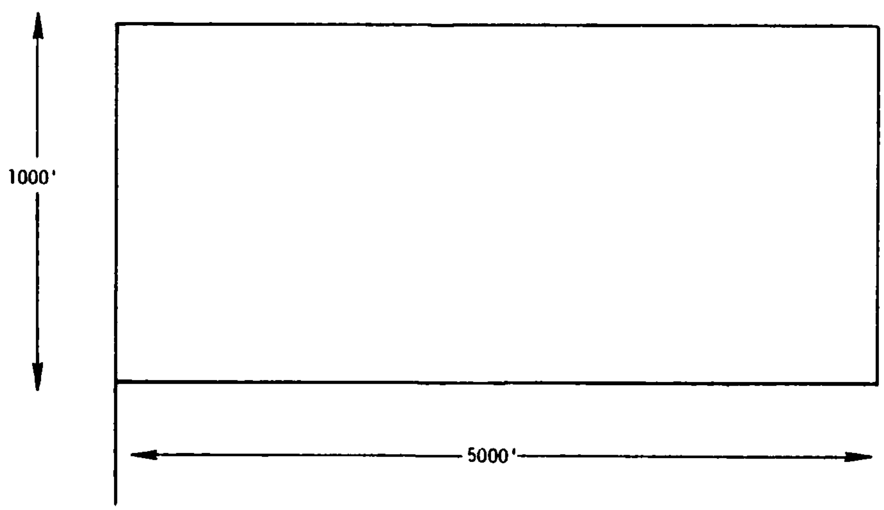

Figure 5.1(b) Maneuver Area B

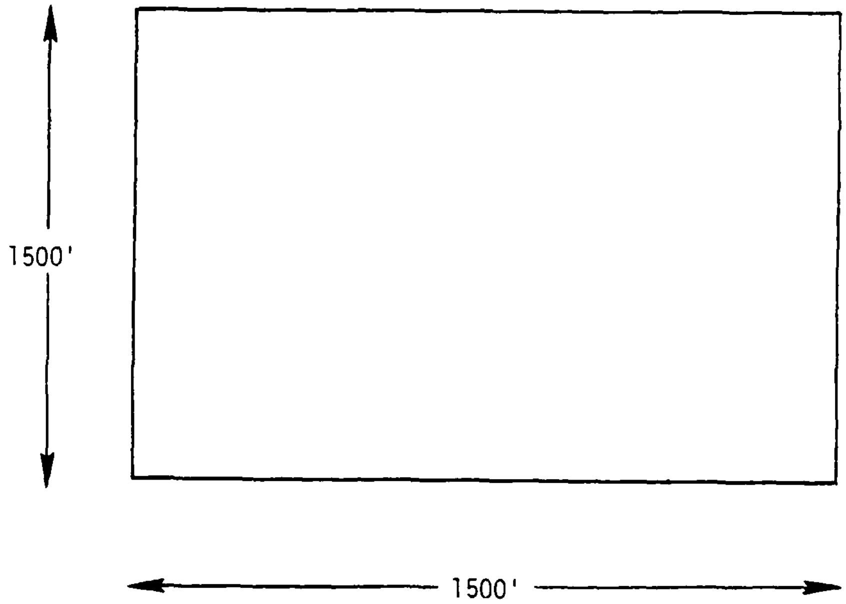

Figure 5.1(c) Maneuver Area C

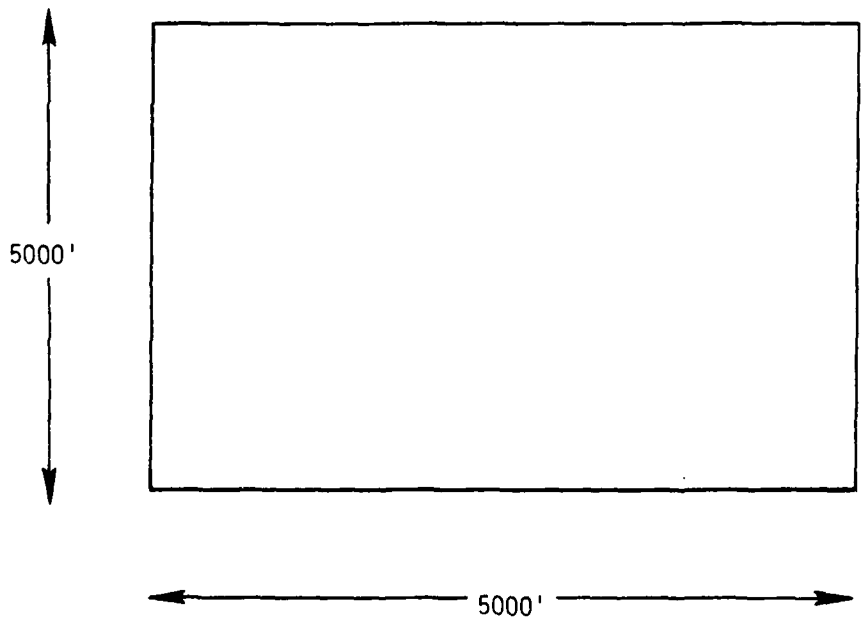

Figure 5.1(d) Maneuver Area D

- Execute narrow (rudder = 40°) accelerating turns in maneuver area C.

- execute bow thruster maneuver in area B.

Each of the 63 maneuvers of Table 5.2 to be performed should be executed at least twice. This is to allow model validation using the prediction error criterion. The identified model should be evaluated by using it to predict data from maneuvers not used directly to estimate parameter values.

Table 5.3 lists the total time required to execute maneuver sequences at various levels of priority. Table 5.3 assumes the following:

- Each maneuver at each of the three priority levels will be executed twice.

- One-half hour of utility maneuvering time is allowed between each test maneuver. Utility maneuvers are simply those which must be executed to set the tow up for the next test maneuver. For example, a 180° turn will be required at the end of each zig-zag maneuver executed in maneuver geometry A.

5.3 TEST AREA

5.3.1 Requirements

The following characteristics are requirements of a test area.

- The test area must be large enough to enclose the maneuver geometries of Section 5.2.

- Immediate USCG requirements are for simulation of river tow motion in deep water. The water depth in the test should be sufficient so that shallow-water effects do not affect tow motion.

- Waterway traffic must be sparce enough to allow the execution of the test maneuvers without endangering the tow or other traffic.

Table 5.3

Time Required to Execute Maneuver Sequences

	TEST MANEUVERING TIME (HR)	UTILITY MANEUVERING TIME (HR)	TOTAL
Priority 1 Maneuvers only	10.	20.	30.
Priority 1 and 2 Maneuvers only	22.	40.	62.
Priority 1,2, and 3 Maneuvers	32.	54.	86.

- If precision radio tracking is to be used to measure tow motion, then secure positions for placement of radio transponders are required.
- Water current shears should not exceed those studied in Section IV.
- The test site must be a part of the U.S. inland waterways accessible to river tows.

5.3.2 Candidate Sites

Two candidate sites for conducting maneuver trials are Lake Pontchartrain and the Barkley Dam pool. Both areas are large enough to contain maneuver geometries A through D. The Barkley Dam pool is located on the Cumberland River near Grand Rivers, Kentucky. This area is possibly the more favorable site for the following reasons:

(1) The water depth is deep with respect to the draft of a typical river tow. Shallow water effects will not affect estimated values of hydrodynamic coefficients. The most immediate U.S. Coast Guard requirement is for the simulation of river tows maneuvering near bridge pilings. Such pilings are usually in relatively deep water.

(2) Water current levels in the pool are very low unless the dam is generating hydroelectric power. It would be desirable to execute tests while current levels are low.

Lake Pontchartrain is a candidate shallow-water test area. This lake has a fairly flat bottom with an average depth of about 13 feet. Testing here would provide data for the estimation of hydrodynamic coefficients valid for that specific depth. Determination of coefficients for depths between 13 feet and the deep depth would need to be done by interpolation or by testing at a different site.

VI. SUMMARY

This report presents a test plan for collecting data for the estimation of hydrodynamic coefficients from maneuvering trials data from a river barge/tow flotilla. The test plan includes a schedule of maneuvers to be executed and a set of sensor type and accuracy requirements. Specific conclusions are as follows:

(1) The use of system identification data processing of full-scale trials data can make unique contributions to the fidelity of ship maneuvering simulators. In particular, it can resolve presently unanswered questions regarding scale effects and model structure.

(2) Any of the hydrodynamic model structures commonly in use by the ship simulation community are suitable for use with system identification estimation methods.

(3) Several candidate sensor systems for instrumenting the trials are feasible. The best overall system is one that uses an aided inertial reference system. Other good systems include three which use combinations of Doppler sonar, accelerometers, and yaw rate gyros.

(4) A satisfactory test plan could be executed by the tow in about 30 hours of testing. (The 30-hour time period includes time following each test maneuver to set up for the next test.)

(5) Two candidate tests sites are: (a) Barkley Dam pool (deep water) and (b) Lake Pontchartrain (shallow water).

REFERENCES

1. Petrie, G.L., "Simulation of Bridge Collision Incidents Involving Inland Waterway Tows: Program Users Documentation," Final Report No. CG-D-49-78, prepared for U.S. Coast Guard Office of Research and Development under Contract DOT-CG-72402-A, June 1978.

2. Petrie, G.L., "Simulation of Bridge Collision Incidents Involving Inland Waterway Tows" Final Report No. CG-D-49-78, prepared for U.S. Coast Guard Office of Research and Development under Contract DOT-CG-72402-A, June 1978.

3. Petrie, G.L., "Simulation of the Maneuverability of Inland Waterway Tows," Department of Naval Architecture and Marine Engineering Report No. 186, University of Michigan, Ann Arbor, MI 48109, August 1976.

4. Schuffel, H., Vermeulen, L., van Breden, L., "Ergonomisch onderzoek open hartel kanaal' Deel II - Be paling van de bewegingsvergelijkingen in het platte vlask voor een lege dunweenheid," Institunt Voor Zin tuigfysiologie TNO Rapport No. IZF 1978-C3, 1978.

5. Miller, E.R., "The Prediction of River Tow Maneuvering Performance," Final Report No. CG-D-32-78 for U.S. Coast Guard Office of Research and Development under Contract No. DOT-CG-72701-A, May 1978.

6. Trankle, T.L., "Practical Aspects of System Identification," ASME Winter Annual Meeting Paper 79-WA/DSC-23, December 9, 1979.

7. Gupta, N.K., Hall, Jr., W.E., Trankle, T.L., "Advanced Methods of Model Structure Determination from Test Data," J. Guidance and Control, Vol. 1, No. 3, May-June 1978, pp.197-204.

8. Faltinsen, O.M., "Theoretical Seakeeping, A State of the Art Survey," International Symposium on Advances in Marine Technology, 1979.

9. Newman, J.N., "Theoretical Methods in Ship Maneuvering," International Symposium on Advances in Marine Technology, 1979.

10. Bourianoff, G.I., Penumalli, B.R., "Computational Prediction of Ship Motion in Confined Waters using Inertial Marker Particles," Austin Research Associates, Inc., Report No. MA-RD-940-77084, June 1977.

11. Mandel, P., "Ship Maneuvering and Control," Principles of Naval Architecture, Society of Naval Architects, New York, 1967.

12. Goodman, A., Gertler, M., Kohl, R., "Experimental Techniques and Methods of Analysis Used at Hydronautics for Surface Ship Maneuvering Predictions," Hydronautics, Inc. Technical Report 7600-1, presented at Eleventh ONR Symposium on Naval Hydrodynamics, London, UK, April 1976.

13. Astrom, K.J., Kallstrom, C.G., "Identification of Ship Steering Dynamics," Automatica, Vol. 12, pp.9-22.

14. Abkowitz, M.A., "System Identification Techniques for Ship Maneuvering Trials," Office of Naval Research Conference on Applications of Control Theory to Navy Problems, Monterey, CA, July 1975.

15. Scragg, C.A., "Determination of Stability Derivatives by Impulse-Response Techniques," Marine Technology, Vol. 14, No. 2, July 1977, pp.265-275.

16. Eda, H., "Equations of Motion for the Ship-Handling Simulator and Proposed Program for Acquisition of Hydrodynamic Data," Davidson Laboratory, Stevens Institute of Technology, Hoboken, N.J., Report SIT-DL-71-1572, November 1971.

17. de Boor, C., A Practical Guide to Splines, Springer-Verlag, New York, 1978.

18. Chen, H.H., "An Investigation of the Sensitivity and the Linearity of Response of a Steered Ship," Office of Research Services, University of California, Berkeley, Final Report under Office of Naval Research Contract No. NONR-3656(17), February 1967.

19. Trankle, T.L., Notes on SNAME H-10 (Hydrodynamics-Maneuverability) Panel Meeting, Washington, D.C. 12 December 1979.

20. Gupta, N.K., Hall, Jr., W.E., "Design and Evaluation of Sensor Systems for State and Parameter Estimation," J. Guidance and Control, Vol. 1, No. 6, November-December 1978, pp.397-403.

REFERENCES (Concluded)

21. Schulz, R.M., "River Tow Behavior in Waterways - Exxon Test Program," Final Report to U.S. Army Engineers Waterways Experiment Station, P.O. Box 631, Vicksburg, Mississippi 39180, under Contract No. DACN39-77-M-0625, 15 July 1977.

22. Schulz, R.M., "River Tow Behavior in Waterways - Second Exxon Test Program," Final Report to U.S. Army Engineers Waterways Experiment Station, P.O. Box 631, Vicksburg, Mississippi 39180, under Contract No. DACN39-77-C-0086, 30 June 1978.

23. Gill, A.D., "The Identification of Maneuvering Equations from Sea Trials Results," Royal Institution of Naval Architects Paper W1 (1975).

LMED

8